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STUDY AND DEVELOPMENT OF AN INTEGRATED HEAD-UP DISPLAY.(U)
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STUDY AND DEVELOPMENT OF AN INTEGRATED HEAD-UP DISPLAY

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JUNE 1981
Final Report for Period 1 July 1976 – 31 Aug 1980

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AVIONICS LABORATORY
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-81-1042	2. GOVT ACCESSION NO. AD-A104337	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STUDY AND DEVELOPMENT OF AN INTEGRATED HEAD-UP DISPLAY		5. TYPE OF REPORT & PERIOD COVERED Final report ~~for period~~ 1 July 1976 ~~to~~ 31 August 1980
		6. PERFORMING ORG. REPORT NUMBER D6210
7. AUTHOR(s) M. N. Ernstoff		8. CONTRACT OR GRANT NUMBER(s) F33615-76-C-1243
9. PERFORMING ORGANIZATION NAME AND ADDRESS Liquid Crystal Development Staff, Display Systems Laboratory, Hughes Aircraft Company, 2000 E. Imperial Hwy., El Segundo, CA. 90245		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2003 06 26
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Wright Aeronautical Laboratory (AFWAL/AAAT) Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE June 1981
		13. NUMBER OF PAGES 102
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Liquid Crystal Display, Flat Panel Display, Diffraction Optics, Head-Up Display, Matrix Display

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of the Integrated Head-Up Display (I-HUD) program was to demonstrate the advantages associated with using a Liquid Crystal Matrix Display and Diffraction Optics combiner in the design and construction of a high brightness head-up display system. The program resulted in the design and fabrication of the I-HUD brassboard consisting of a pilot's display unit, built in a form factor similiar to that of the production F16 HUD, and test support equipment. The following devices and modules were developed:

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A 350-by-350 pixel Liquid Crystal Matrix Display complete with custom LSI circuit drivers, a diffraction optics combiner, a diffraction optics diffusing screen, a specular mode projector, and custom lamp with a narrow band (green) spectral output. Although the completed I-HUD brassboard did not meet all of its design goals, it does demonstrate the feasibility of applying advanced technology to the designs of Head-Up Displays. The I-HUD program has succeeded in solving many of the fundamental design problems associated with this approach and stands as a milestone in the development of solid state display devices and the development of more highly reliable, cost effective Head-Up Displays.

The I-HUD is the first HUD to be built which uses a solid state matrix display and is also the first HUD which is fully compatible with a standard RS-170 television raster interface rather than the commonly used, non-standard analog stroke interface.

Some of the technical advances made on the I-HUD program are applicable to directly viewed solid state displays.

Contract Number F33615-76-C-1243

1 July 76 - 31 August 1980

"STUDY AND DEVELOPMENT OF AN INTEGRATED HEAD-UP DISPLAY"

PREFACE

The successful completion of the Integrated HUD (I-HUD) program was the result of an interdisciplinary team effort by individuals from widely separated areas of Hughes Aircraft Company. The Display Systems Laboratory, Radar Systems Group, provided overall program management, project system engineering, and design staff for the electronic and mechanical tasks. The Display Products area of the Industrial Products Group was responsible for the design, fabrication and testing of the Liquid Crystal Matrix Display and its custom LSI drivers. In this work, these groups were supported by the Optical Design Section of the Electro-Optical and Data Systems Group, and the Connecting Devices Division of the Industrial Products Group. The Electro-Chemistry section of the Hughes Corporate Research Laboratories formulated the liquid crystal material.

The team of individuals whose consciencius efforts contributed to the completion of the I-HUD program included: Richard Bernstein, William Byles, Lacy Cook, Jim Cooper, Michael Ernstoff, John Ferrer, Bruce Fletcher, John Gunther, Chick Hines, William C. Hoffman, Herb Kamera, Jim Keenan, Dave Kuscienka, Anna Lackner, William Lichty, Lew Lipton, Michael J. Little, Randy Lloyd, Mark Lund, J. David Margerum, Wilson Quan, Steve Shields, Harvey Spencer, Craig Stephens, Andy Toth, Richard Winner, Roger Withrington, and Terry Zimmerman. The program was monitored and directed by John Mysing and John Coonrod of the System Avionics Division of the Avionics Laboratory - a division of the Air Force Wright Aeronautical Laboratories, Wright Patterson Air Force Base, Dayton, Ohio.

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INTRODUCTION AND SUMMARY

1. BACKGROUND

The performance and reliability of present head-up display (HUD) designs are limited by the brightness, resolution and positional stability of the CRT image source as well as the efficiency of conventional optical components. In addition, current head-up display (HUD) design practices stress the cathode-ray tube (CRT) and its associated circuitry up to and beyond the limits of reliable design, thus imposing high support costs. The substitution of a liquid crystal matrix display for the cathode ray tube removes the brightness-resolution tradeoff restraint and provides digitally specified symbol positions for improved armament aiming reliability.

Hughes began the development of the liquid crystal matrix display in 1972 as an alternative to the conventional CRT for the presentation of symbolic, graphic, and pictorial images in military applications. This report describes the results of the Integrated Head-Up Display (I-HUD) program, the second major program aimed towards the development of a liquid crystal matrix display for the presentation of pictorial information. This report is organized so as to present a summary of the design in this introductory chapter, and a review of the performance in the second chapter, while subsequent chapters detail the work that was necessary to implement and support the selected design approach. The report ends with a set of conclusions and recommendations. Finally, appended to this report is a bibliography of published papers that will be of interest to the reader seeking additional background information on the liquid crystal matrix display.

In preparing this report, the philosophy used was to provide a document which would aid in understanding the operation of the I-HUD unit and the trade-offs made during its design. To completely describe the equipment in detail, this report would have to include a discussion of each of the (approximately) 150 D-size (34 by 22 inch) drawings that were made to specify the characteristics of components and subassemblies. The complexity of the I-HUD system design is indicated by the large number of drawings that were drafted because they were needed and not because documentation was required by a contractual line item. Appended to this report are two lists of these drawings, one sorted by drawing number and another sorted by title.

2. ACCOMPLISHMENTS

The I-HUD project was a very ambitious program. Five state-of-the-art technologies were functionally integrated and physically packaged into a single system; they were:

Liquid Crystal Matrix Display. Solid state liquid crystal matrix displays of 350 x 350 resolution (122,500 picture elements) were built at a density of 100 elements per inch. This density is the highest achieved by any solid state display technology to date: 64-elements/inch is typically quoted as the state-of-the-art resolution density for electro-luminescent (EL) and light-emitting diode (LED) display technologies. Current work at Hughes has extended liquid crystal matrix display denisty to 321 elements per inch.

LSI Matrix Display Drivers. Custom LSI drivers were designed and fabricated to drive the 350 rows and 350 columns of the liquid crystal matrix display. The 38-watt power consumption of these drivers (which are of the first design iteration) and their basic support circuitry is less than that of comparable military CRT deflection amplifiers.

Diffraction Optics. A special rear projection screen was fabricated that is especially efficient in diffusing and directing the light from the specular mode projector. Its very high screen gain and low backscattering means that it will also find application in providing a high contrast, sunlight viewable, head-down display.

High Efficiency Thallium Iodide Arc Lamp. A 50-watt xenon arc lamp was developed in which thallium iodide was used as an additive to increase the conversion efficiency for green light. The luminous efficiency of the lamp is better than 16 lumens per watt for conversion to green light within the narrow band between 531 and 539 nanometers.

Specular Mode Liquid Crystal Projector. The liquid crystal specular mode projector was developed to efficiency collect and spatially modulate (using the liquid crystal matrix display) the light radiated from the lamp. With this projector, a screen brightness of 1700 foot-lamberts was obtained using only 50-watts of lamp power. This brightness level is an order of magnitude greater than that which is currently achievable by other solid state display technologies of comparable complexity. Moreover, this brightness value could be increased several fold by execution of improvements to existing techniques.

All of the aforementioned subsystems were packaged into a unit approximately the same size as the F-16 production HUD in order to demonstrate that the system integration could be accomplished in a realistic volume.

The I-HUD is the first head-up display to use a standard raster interface and still achieve high brightness. The I-HUD eliminates the need for a stroke function in the symbol generator, and thus the speed of the symbol generator is no longer paced by the response time of the deflection amplifier. In addition, a direct interface to FLIR, TV, and other raster compatible sensors is now possible.

Finally, the I-HUD program has contributed to the design of a production HUD system. USAF personnel became familiar with the advantages of diffraction optics when monitoring the I-HUD program, and as a direct result, they subsequentially selected an approach based on that technology for use in the Low Altitude Navigation and Target Infra Red for Night (LANTIRN) HUD program.

3. DESIGN OVERVIEW

The I-HUD Brassboard System consists of two units of hardware, the Pilot's Display Unit and the Test Support Equipment. The design and fabrication of the Pilot's Display Unit was the primary contractual obligation; it contains all of the state-of-the-art components and its operation illustrates how they can be used together advantageously. A photograph of the I-HUD Pilot's Display Unit (complete except for the rear cover) is shown in Figure 1. The Test Support Equipment contains the power supplies and circuitry necessary to operate the Pilot's Display Unit in a laboratory having standard 60 hz power and conventional TV or calligraphic symbology signal sources.

The Pilot's Display Unit constitutes the essence of the I-HUD system and its design constituted the bulk of the contractual effort. In designing the I-HUD brassboard, the primary emphasis was on demonstrating how liquid crystal matrix displays and diffraction optics could be combined in a Head-Up Display system in a manner that would provide significantly increased brightness and reliability. Compromises were made in resolution and field-of-view in order to limit the scope of the effort. A functional breakdown of the resulting Pilot's Display Unit design is illustrated in Figure 2, and a summary description follows. As the design of the Test Support Equipment is entirely conventional, no overview has been prepared, and readers desiring a description of it are referred to the chapter specifically devoted to that equipment.

A diffraction optics combiner is used to maximize combiner see-through, symbol brightness, and instantaneous field of view. The combiner has been designed to function as a reflector within a narrow band around 535 nanometers, and as a result it is transparent over most all of the spectrum. The combiner was designed to transmit 95-percent of the visible spectrum and to reflect 75-percent of the narrow bandwidth symbol luminosity. The optical ray traces for the final design are shown in Figures 3 and 4.

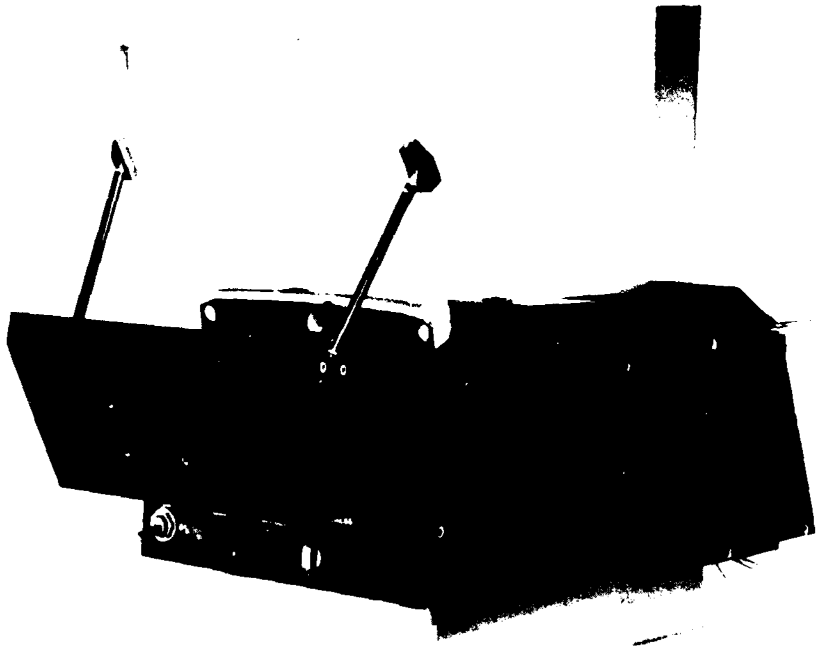


Figure 1. Photograph of Pilot's Display Unit.

The relay lens provides for· correcting the optical abberations introduced by the off-axis diffraction optics combiner. Its design has been iterated with that of the diffraction optics combiner so as to reduce to below one milliradian the residual optical errors such as spherical and field curvature (causes binocular disparity), coma (impacts accuracy), and astigmatism (impacts resolution).

The diffraction optics diffusing screen was used so that high screen gain and uniform brightness could be obtained simultaneously with the sharp bend angle required for the combiner by the F-16 installation constraints. The screex is a holographic recording of an illuminated diffuser, and the exposure apparatus (construction optics) has been designed so that the light from the projector is diffracted by the screen only into the area that corresponds to the entrance pupil of the

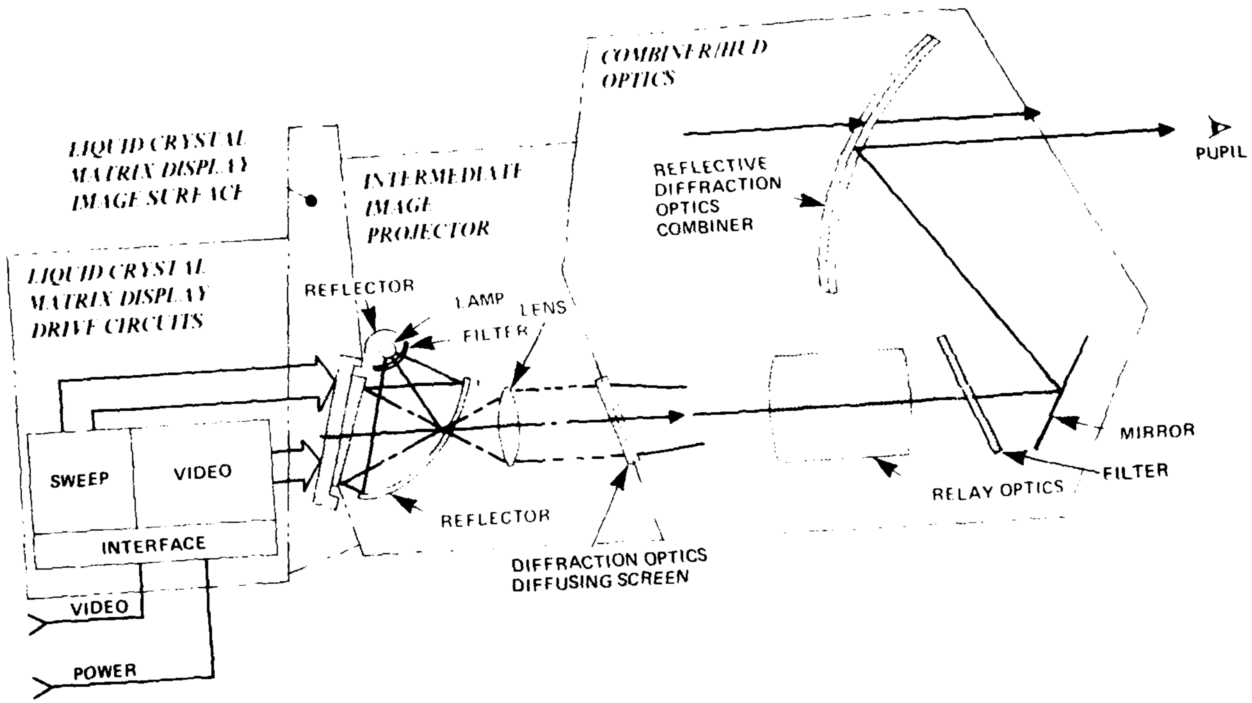


Figure 2. Pilot's Display Unit functional blocks.

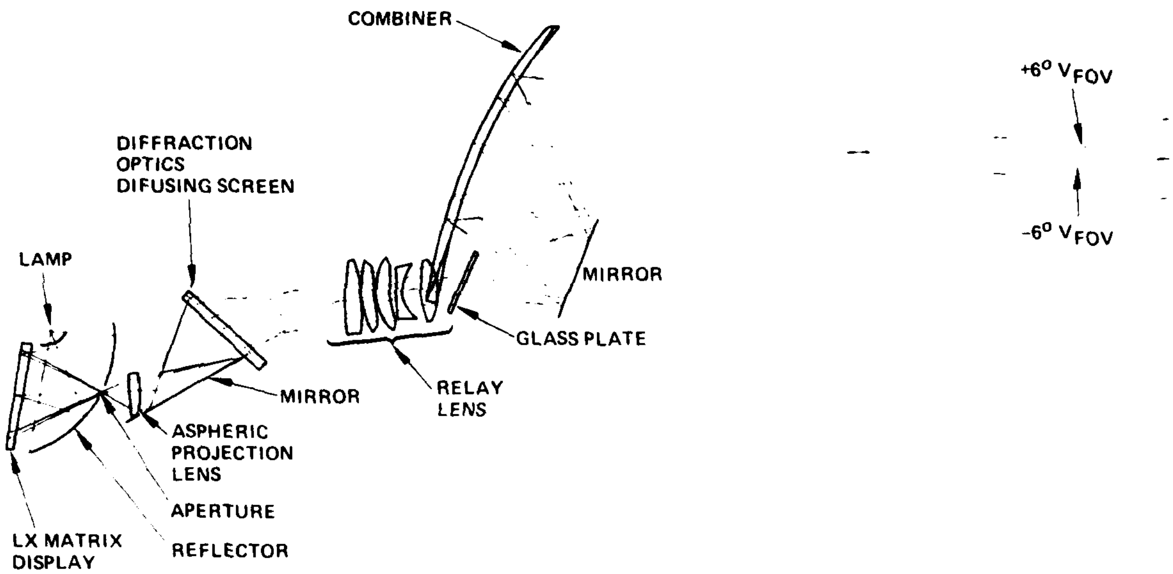


Figure 3. Vertical cross-section of optical layout.

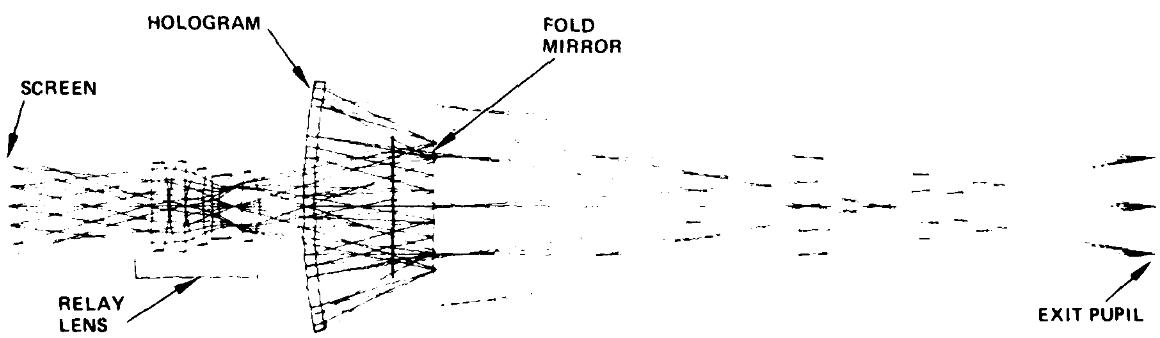


Figure 4. Horizontal cross-section of optical layout.

relay lens. If light were scattered outside the entrance pupil of the relay lens, energy would be wasted; by directing most of the light to within the entrance pupil of the relay lens, a diffraction optics diffusing screen increases significantly the screen brightness that can be obtained for a given level of incident light flux before the brightness variations across the field of view become a problem as with conventional diffusing screens.

To maximize the brightness of the symbology, the projector was designed to collect a large portion of the light from the lamp and to permit the light to be spatially modulated in an efficient manner. A specular projector configuration was chosen because with it a dynamic scattering liquid crystal display can be used to efficiently modulate the light and produce the requied image contrast. Those areas of the liquid crystal matrix display that are "off" specularly reflect their portion of the illuminating light thru the aperture hole and onto a corresponding position on the screen. Those areas of the liquid crystal matrix display that are "on" scatter their portion of the illuminating light; little of it passes through the aperture, and the corresponding position on the screen is dark. The specular projector approach provides high screen brightness because all of the light gathered from the projection lamp is used to illuminate the screen with the exception of losses at the surfaces of the optical elements. The projection lens is provided to shorten the throw distance and to prevent degradation of the image resolution when the aperture is larger than the ideal pin hole.

The projection lamp has been designed to be an intense source of nearly monochromatic green light. The output of the thallium-iodide doped xenon arc lamp is substantially all concentrated in a very narrow band around 535 nanometers, and the design of the diffraction optics diffusing screen and the diffraction optics combiner has been optimized for this wavelength. Since the minimum aperture size is proportional to the size of the lamp arc length, and the contrast ratio of the liquid crystal matrix display in a specular mode projector is inversely proportional to aperture size, an arc lamp having small electrode spacing was developed.

A liquid crystal matrix display presents dynamic shades-of-gray television images by inducing dynamic scattering in selected areas of a thin film of liquid crystal material. The material is sandwiched between a transparent conductive cover (usually indium-tin oxide coated glass) and an array of reflective electrodes formed on the surface of a silicon semiconductor substrate. The electrical potential of each elemental electrode is controlled by a matching array of transistors and capacitors formed in the surface of the silicon substrate by standard metal-oxide-semiconductor (MOS) processing techniques. These transistors and capacitors form an X-Y grid of sample and hold circuits that allow each picture element of the display to be individually addressed in rapid succession. Since the magnitude of the scattering is proportional to the applied potential, grey scale information can be presented in raster format when suitable circuitry is provided to drive the rows and columns of the display.

A physical quad display provides increased resolution by combining four electrode-array modules in a two-by-two quad module mosaic array. The four modules are mounted onto a common substrate and a single transparent electrode covers the entire array area. Electrical connection is made on all four peripheral edges; there are no interconnections between the rows and columns of separate modules.

The drive circuits allow a simple electrical interface to be used between the Pilot's Display Unit and the power/signal source. The sweep drive circuits incorporate shift registers and buffer amplifiers to sequentially enable each row of the display. The video drive circuits utilize two sets of analog data bins to sequentially store the serially presented video data; the accumulate and disseminate functions are alternated so that while one line of video data is being stored, the prior line is being presented in parallel synchronous format to all columns of the display. Thus analog signals for driving the many rows and columns of the display are derived from a single video signal and a few synchronization signals.

The form factor of the Pilot's Display Unit Package is nearly the same as that of the existing F-16 production HUD. The photograph shown in Figure 5 illustrates the Pilot's Display unit with its sheet metal covers removed.

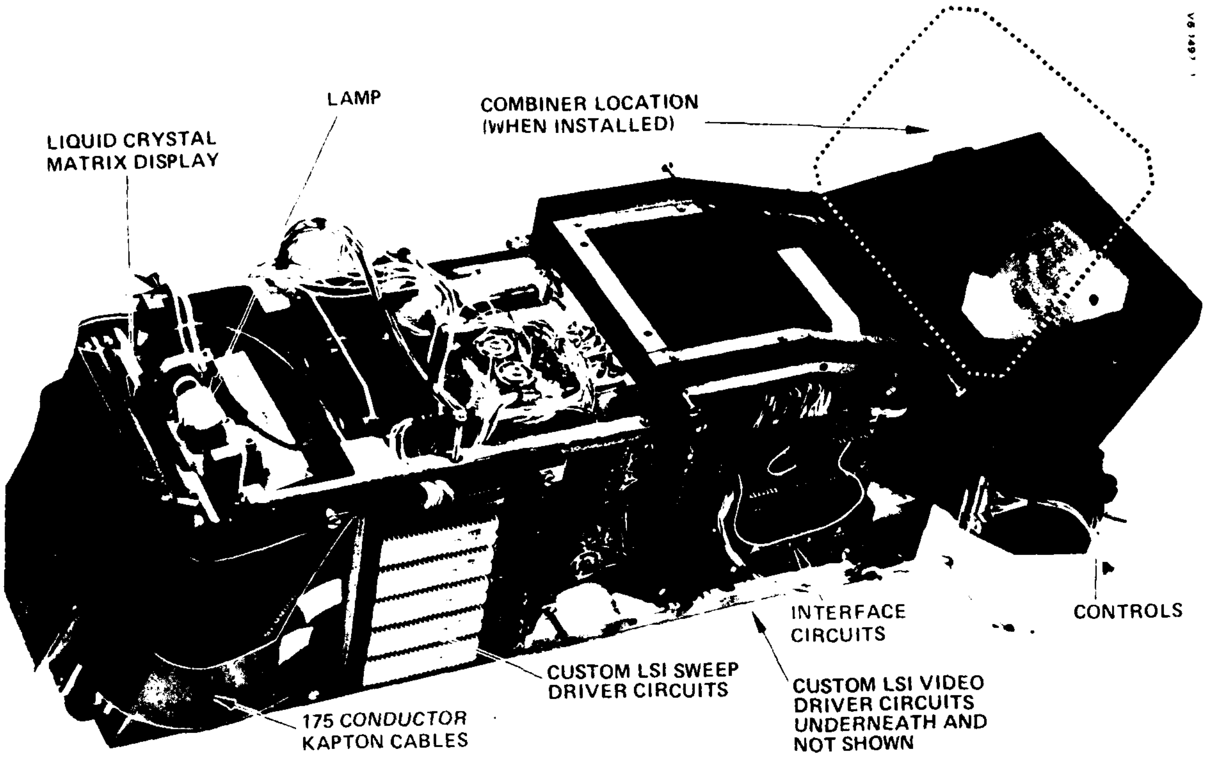


Figure 5. Pilot's Display Unit with covers removed.

SECTION II.

SYSTEM PERFORMANCE

The performance of the I-HUD system represents a significant step forward in the design of head-up display systems. The I-HUD brassboard represents the first serious attempt to combine liquid crystal matrix display with diffraction optics to produce an improved head-up display system. Completing this effort required the development of entirely new designs in five areas: (1) Liquid crystal matrix displays, (2) LSI circuit drivers for the matrix display, (3) Specular mode projectors for displays using dynamic scattering liquid crystal materials, (4) Thallium- iodide doped xenon-arc lamps, and (5) Diffraction optics diffusing screens. The I-HUD system works; it is not yet optimized, but the problems from this point on are well understood and the solutions are straight forward. Firm projections can now be made as to ultimate performance, and the optimum design approach appears to be close at hand.

Field-of-view. The instantaneous field-of-view (FOV) is determined by the size of the combiner and the distance between it and the viewer. The combiner is 7.5 by 6 inches which results in an instantaneous field of view for a 26-inch viewing distance of 16-degrees azimuth and 12-degrees elevation. The total field-of-view includes the additional area that can be seen by moving about in the exit pupil. The total field-of-view is limited by the size of the intermediate image on the diffusing screen and the elements in the relay lens. The I-HUD has a total field-of-view that is 20-degrees in azimuth and 14.5-degrees in elevation.

Exit Pupil Size and Pupil Illumination Uniformity. The optics in the I-HUD provide a pupil forming system, so the viewer (pilot) must position his eyes within the exit pupil of the system to see the imagery on the combiner. The uniformity of pupil illumination across the design exit pupil is compromised by an error in the fabrication of the diffraction optics diffusing screen; the exit pupil of the diffraction optics diffusing screen is not properly positioned at the entrance pupil to the HUD relay optics. As a result, the field-of-view is partially vignetted when the observer is not centrally positioned within the exit pupil. The design called for the exit pupil to be a 3.5-inch diameter circle truncated at plus and minus 1.5 inches. With a new diffusing screen having a corrected located exit pupil, the I-HUD would provide this performance.

Resolution. The liquid crystal matrix display has 350-by-350 picture elements which corresponds to one milliradian per picture element in the field-of-view of the combiner. Although 350 by 350 picture elements may be inadequate for an operational system, it is sufficient to demonstrate the validity of the I-HUD concept. This resolution does not represent the current state-of-the-art, but rather that which existed at the start of the I-HUD program.

Brightness. The anticipated symbol brightness (in the combiner) based on the initial design analysis was 2800 ft-lamberts. The highest brightness measured was 1000 ft-lamberts. Figure 6 illustrates what factors were used for

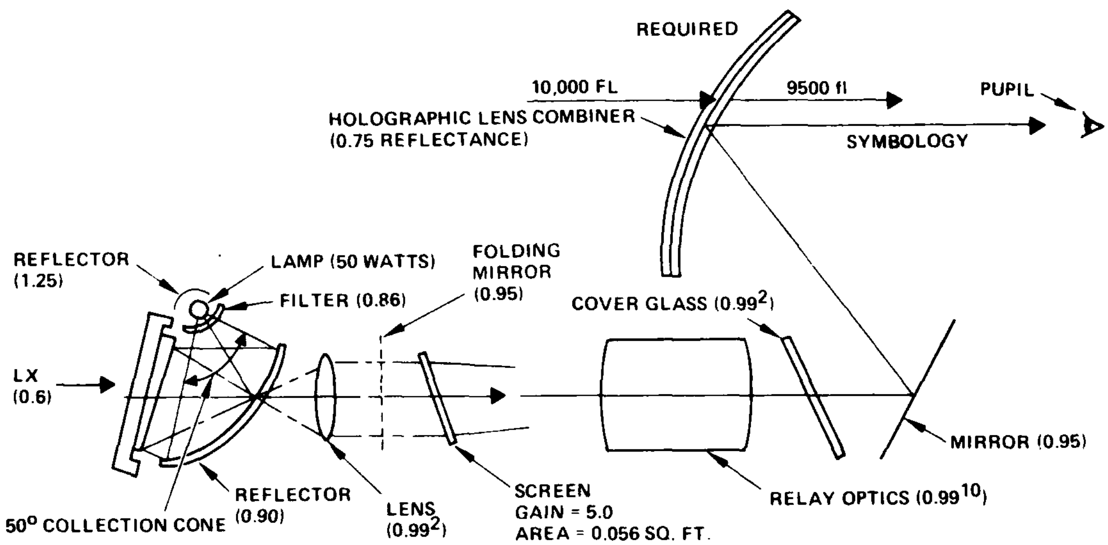


Figure 6. Basis for brightness analysis.

the initial brightness analysis, and Table 1 summarizes the brightness performance based on these factors. Note that between the initial design and the final design, two folding mirrors were deleted from the optical path. By comparing Table 2 with Table 1, one can assess why the actual performance fell short of the design value. Retrofitting a higher efficiency diffusing screen could increase the brightness by several times over the present performance.

Contrast Ratio and Background Glow. The basic design concept was known to be capable of achieving very high contrast ratios with the proper optical surfaces, and Figure 7 illustrates that contrast ratios in the 100:1 range are

TABLE 1.

INITIAL BRIGHTNESS ESTIMATE

LAMP		
Input Power	50 Watts	
Conversion Efficiency	15.5 lumens/watt	
Radiated Light	775 lumens	
Reflector Collection Efficiency	20 percent	
Spherical Mirror Boost	125 percent	
Filter (UV/IR) Attenuation Factor	0.86	
Collected	170 lumens	
PROJECTOR		
Reflector Reflectance	0.90	
Display Surface Reflectance	0.50	
Aperture Transmission	1.00	0.42
Projector Lens Attenuation	0.98	
Folding Mirror Reflectance (0.95^2)	0.90	
Projector Output	70 Lumens	
SCREEN		
Screen Area	0.056 sq. ft.	
Screen Gain (80% of 5)	4.0	67 ftL/Lumen
Folding Mirror Reflectance	0.95	
Screen Brightness	4500 foot lamberts	
HUD		
Relay Lens Attenuation	0.904	
Cover Glass Attenuation	0.98	
Folding Mirror Reflectance	0.95	0.63
Combiner Reflectance	0.75	
Symbology Brightness	2800 foot lamberts	

TABLE 2.

REVISED BRIGHTNESS ESTIMATE

LAMP	
Input Power	60 watts
Conversion Efficiency	17.0 lumens/watt
Radiated Light	1000 lumens
Reflector Collection Efficiency	20 percent
Spherical Mirror Boost	125 percent
Filter (UV/IR) Attenuation Factor	0.75
Collected Light	250 lumens
PROJECTOR	
Reflector Reflectance	.50
Display Surface Reflectance	.60
Aperture Transmission	.20 } 0.06
Projector Lens Attenuation	.98
Folding Mirror Reflectance	.95
Projector Output	15 Lumens
SCREEN	
Screen Area	0.056 sq. ft.
Screen Gain	6
Folding Mirror Reflectance	NA
Screen Brightness	1700 foot Lamberts
HUD	
Relay Lens Attenuation	0.904
Cover Glass Attenuation	0.98
Folding Mirror Reflectance	0.85
Combiner Reflectance	0.80
Symbology Brightness	1000 foot lamberts

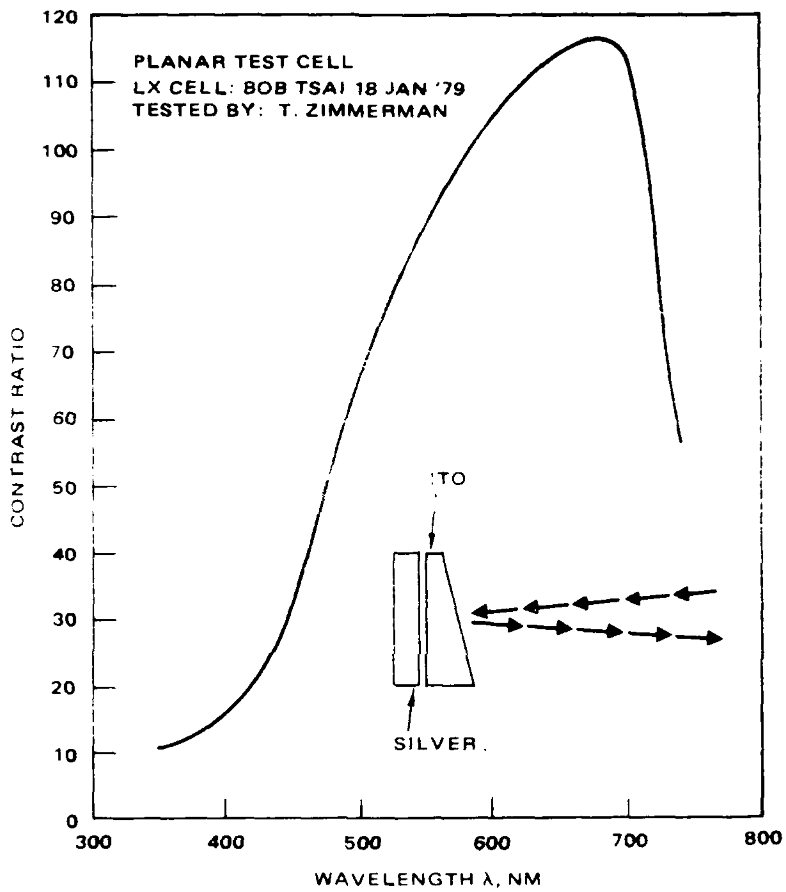


Figure 7. Evidence of high contrast ratio potential.

possible over a limited wavelength range. A contrast ratio of 32:1 had been set as a goal, but only 19:1 was actually achieved. The reduced contrast ratio is due to: (1) too thick an indium tin oxide (ITO) layer - its thickness was inadvertently not reduced to the design value when slant silicon dioxide was substituted for ion-beam etching as the liquid crystal alignment technique, and (2) the surfaces of the liquid crystal display modules were not smoothed.

Background Glow. At night, it is desirable to be able to dim the symbology on the HUD to a very low level so that it does not interfere with the dark adaptation level of the pilot's eyes. With CRT based HUD displays, the glow of the cathode can be sufficient to interfere with night viewing. The I-HUD design assumes the use of a variable attenuator in the optical path for reducing symbol brightness. Experiments confirmed that this approach would reduce the background glow nearly linearly as symbol brightness was reduced. It was found that the contrast ratio of the display degraded to only 15:1 when attenuated such that the symbol brightness was 0.3 ft-lambert against a 0.002 ft-lambert background.

Brightness Uniformity. A detailed analysis was made to estimate brightness uniformity as a function of field-of-view. Unfortunately, this analysis came after most all of the components were substantially fabricated. The results of this analysis is presented in Figure [illegible]. Although detailed data was not taken, the appearance of the I-HUD imagery qualitatively verified the validity of these results. The brightness uniformity of the I-HUD system was further degraded by non-uniformities in the elliptical reflector, and their impact was to introduce circular streaks in the field-of-view. Reflectors without these uniformities are regularly made for high-power projectors, and it seems valid to assume that acceptable quality could be obtained provided one did not have to accept the first unit in a series. It is anticipated that retrofitting an improved reflector would lead to significant gains in brightness uniformity. The other brightness non-uniformities are now well understood and could be balanced out in figure designs.

Defects. The defects in the I-HUD display have been traditionally been classified as element defects, line defects and blemishes. An element defect occurs when one picture element is inoperative. A line defect results when a substantial portion of a row or column is inoperative. A blemish is a defect that is not aligned with the X-Y rectangular structure of the matrix. The photographs presented in Figure 9 show the display before it was inserted into the projector. The line defects are to a large part believe to be caused by shorts induced during the sawing operation. The individual wafers were measured prior to sawing, and there were only 12 line defects in total. Had no more defects been introduced, the quad display would have had only twelve half-line defects. If it is not required to build a physical quad and redundant drive can be provided, recent tests show that high yield of line defect free devices can be obtained by using a laser trimming (or equivalent) technique to convert all shorts to opens.

Speed. The speed of response of the liquid crystal display is specified in terms of the time required to reach 90-percent of the steady state value. The activation time

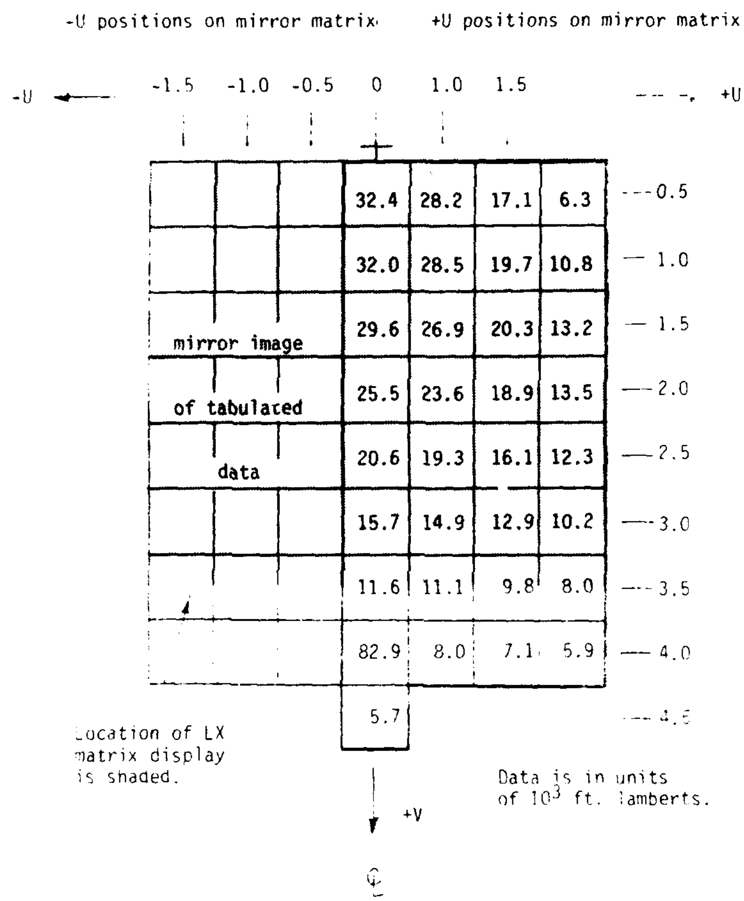


Figure 8. Brightness uniformity analysis.

and the decay time are dependent on separate phenomenon and are not necessarily related. The goal had been to achieve turn-on and turn-off times faster than 100 milliseconds. Actual measurements indicated that the speed was considerably faster; turn-on (dark to bright) and turn-off (light to dark) were 60 and 20 milliseconds respectively.

Size. The goal had been to develop a package that would be physically interchangeable with the production F-16 HUD package. The I-HUD brassboard dimensions shown in Figure 10

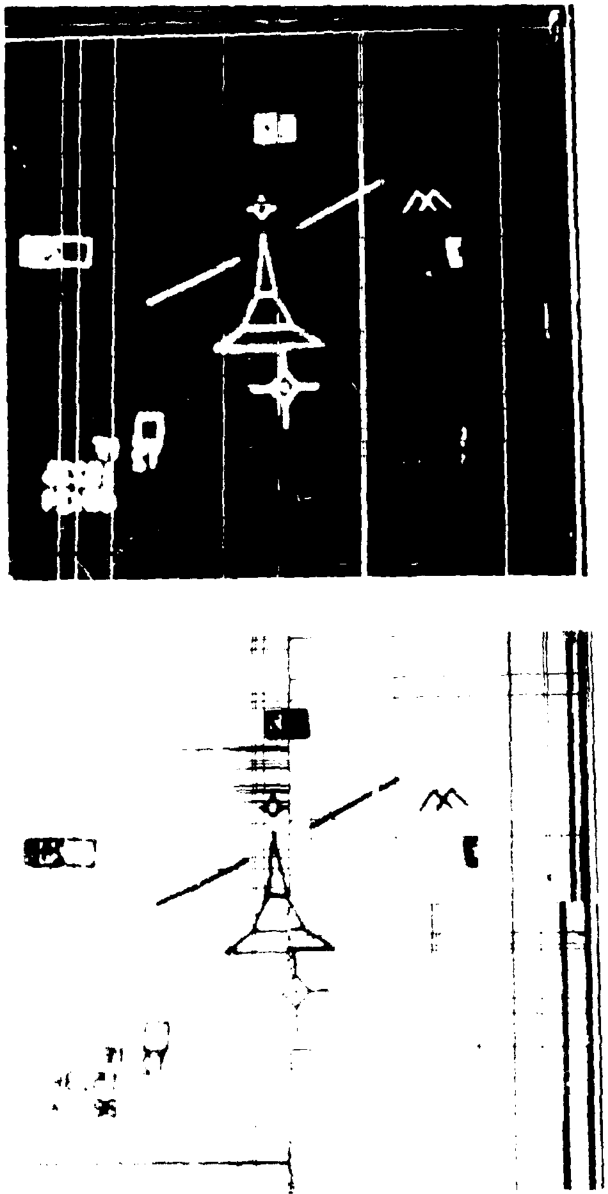
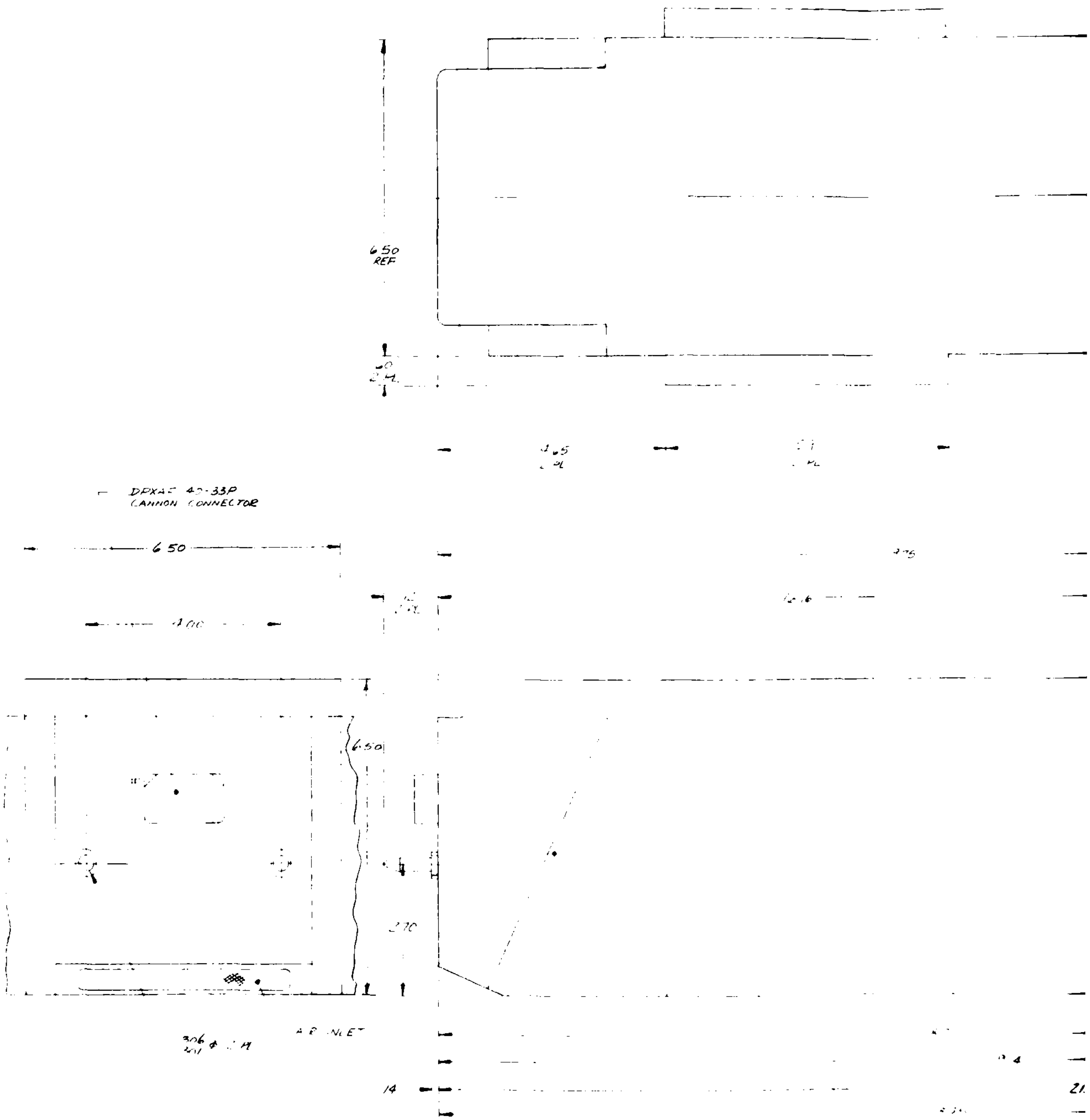


Figure 9. Quad display photos.

are substantially the same as those for the F-16 HUD except for a slight (three inch) increase in length and the two bulges on the side. The length could be decreased by redesigning the optical paths to include additional folds, and the side bulges could be eliminated by redesigning the high density ribbon cables to allow the driver circuits to be relocated.

Weight. The weight of the Pilot's Display Unit is 32 pounds. Although the chassis is made out of aluminum, no other concerted effort was made to reduce weight.



6.50
REF
DPXAE 42-33P
CANNON CONNECTOR
6.50
6.50
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Figure 10. Pilot's Display Unit installation control drawing.

[illegible]

Power Consumption. Power is consumed by the Pilot's Display Unit for three functions: illumination lamp, fans, and electronics. The thallium-iodide lamp is nominally rated at 50 watts, but the total power associated with its use is nearer 75 watts when the inefficiencies in the lamp power supply are included. The fans are rated at consuming 50 watts total under a nominal pressure head; their actual power consumption was not measured. The total power consumption of all the circuitry necessary to support the quad liquid crystal matrix display in the Pilot's Display Unit was measured at 38 watts. In the Test Support Equipment, 8 watts of additional power are required by the circuitry necessary to make the display compatible with standard 525/875-line television interfaces. No concerted effort was made to reduce power consumption other than that required to prevent overheating in space restricted areas.

SECTION III.

WAFER PROCESSING AND TESTING

1. BACKGROUND

The sequence of processing steps used to produce the wafers for the liquid crystal matrix display consists of those used to produce standard metal-oxide semiconductor field-effect transistor (MOS-FET) circuits and the additional steps to produce a smooth reflective electrode structure. The I-HUD display requires four 1.75-inch square modules arranged in a quad format. Each module has an array of 175 x 175 electrodes and addressing circuits at a linear density of 100 elements per inch. The fabrication of the liquid crystal matrix display modules differs from traditional large-scale integrated (LSI) circuits in that (1) each wafer yields only one large circuit chip, (2) the surface of the finished wafer has an electrode structure which must be of optical quality, and (3) the circuits are not particularly defect sensitive because the critical areas are small and sparsely spaced. In designing the I-HUD module, the approach was to: (1) minimize risk by utilizing an approach similar to previous designs, (2) reduce the probability of mask-related defects by utilizing direct pattern generation, (3) improve the yield by incorporating processing improvements based on prior experience, and (4) provide prompt detailed data on wafer quality by mechanized testing.

2. MASKS

A key factor in the design of the liquid crystal matrix display is the layout of the elemental cell which is repeated 175 by 175 or 30625 times on each wafer. The design of an elemental cell involves performing a complex series of trade-offs between desired electrical characteristics and physically realizable dimensions. In designing the elemental cell for the I-HUD, three changes in the previous design were made:

(1) The elemental storage capacitor was split into two sections to eliminate capacitive coupling between adjacent elements. In previous designs, the elemental electrode from one element overlapped the elemental storage capacitor of an adjacent element. The two capacitors are now linked by a common tie to the corresponding elemental electrode.

(2) The edges of all the circuit components were aligned parallel to the orthogonal X-Y addressing grid. In the finished display, these edges generate small spurious

reflections, and it is easier to provide satisfactory illumination and viewing configurations if they are confined to an orthogonal pattern. Also, the elimination of non-orthogonal lines was desired to ease the visual tasks performed by operators of the mask aligning equipment.

(3) The spacing around the p+ boron diffusion was increased to relax alignment and doping level tolerances. Incorrect positioning of this diffusion results in a device with low breakdown voltages. A microphotograph of the I-HUD elemental cell is shown in Figure 11. A photograph of a complete wafer containing a 1.75-inch square matrix is shown in Figure 12.

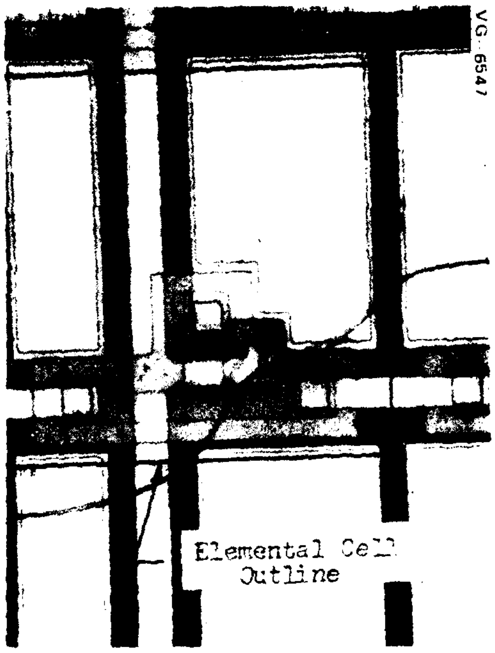

Figure 11. Microphotograph of array addressing circuit element.

Fabrication of the array is accomplished, in part, by successive photolithographic reproduction of the mask layers on the wafer. Thus, it is essential that a perfect mask set, i.e., one that is perfect in terms of geometrical representation, and having no pinholes, bridging, tears, and other common mask defects, be obtained. In previous programs most display blemishes were attributable to mask related defects; perfect photolithographic masks are essential to the economical production of defect-free displays.

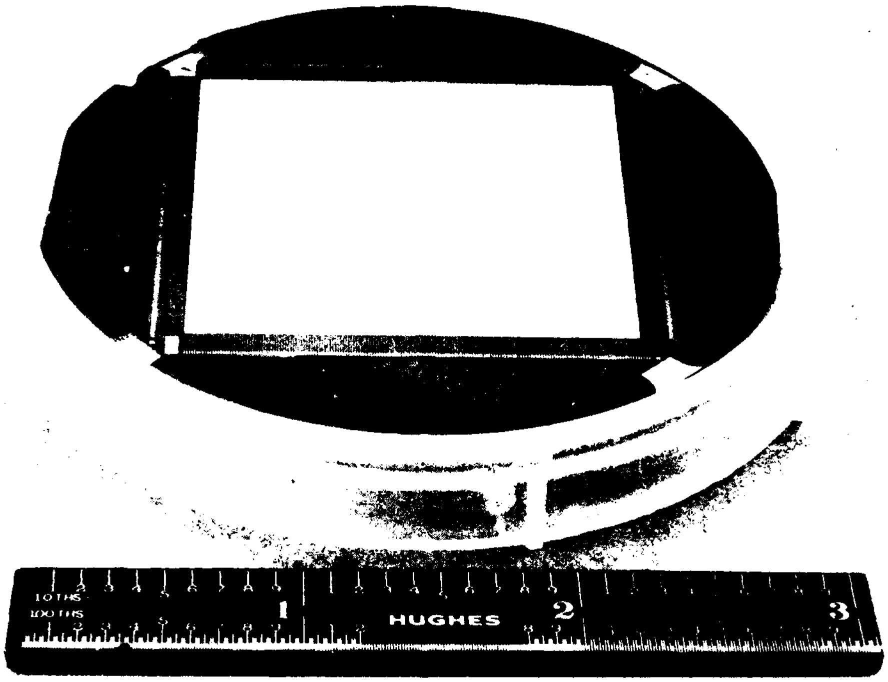

Figure 12. Three inch diameter wafer with 175-by-175 pixel array.

To reduce the probability of mask-related defects on the I-HUD program, a mask vendor was selected that could both directly generate and repair the master masks. Direct generation is the process normally used for making the small 10X reticles; however, it was possible to use this approach in the I-HUD program because of the relatively coarse geometry involved. The master masks were made in their entirety at actual size using a computer controlled X-Y table and an electronic pattern generation machine. This approach eliminated the intermediate reticle step-and-repeat operation and its associated probability for introducing defects.

Mask repairing is accomplished using a laser trimmer to remove mask shorts and a proprietary technique to fill pin holes. Previously, if a mask was found to have a defect, it was discarded and replaced by a new mask. There was no guarantee that the new mask would have fewer defects than the one it replaced. With a mask repairing capability, a defect on a mask can now be eliminated without the need to recheck the entire mask for the introduction of additional defects. Thus, defects can be eliminated in a progressive manner.

3. ADDRESSING CIRCUIT FABRICATION

The transistors and capacitors necessary to X-Y address the individual display elements in the matrix array, and the reflective electrodes are formed in and on the surface of a three-inch diameter silicon wafer. The single module array, when completed, is 1.75-inches square, has a linear density of 100 picture elements per inch, and contains 30,625 transistors and capacitors. This task is accomplished with a high degree of perfection by using precision procedures with the generally uncritical p-MOS processing approach. The sequence of processing steps used to fabricate the addressing circuits and array of reflective electrodes is listed in Table 3.

TABLE 3.

FABRICATION PROCESSING STEP SEQUENCE

Addressing Circuit Fabrication:		
1.	p+ Diffusion	Junction formulation
2.	Thin oxide grown	Gate and capacitor insulator
3.	contact etched	Transistor connections
4.	Polysilicon deposition	Metalization layer
Test -	Characterize performance of	each row and column.
Reflective Electrode Fabrication:		
5.	Deposit oxide	Insulation layer
6.	Via contact etched	Electrode connection
7.	Silver deposition	Reflective electrode
Test -	Characterize performance of	each row and column.

Masking is a recurrent critical step in the addressing circuit fabrication sequence. To eliminate mask wear, projection printing has been used exclusively for all masking operations. To help assure fine results, a new Perkin-Elmer projection mask aligner for three inch diameter wafers was installed just prior to the beginning of the I-HUD program. In addition, careful attention was given to the storage, handling, application, and development of the photoresist. Equipment has been provided for automatic: temperature control and continuous filtering of the photoresist, wafer handling and application of the photoresist by spinning, and timing and temperature control of the photoresist developer solutions. The entire photoresist facility has been designed to significantly reduce processing imperfections and operator errors.

The production of wafers for the I-HUD calls for two critical deposition steps: The deposition of the doped polysilicon metalization layer that is used for the gate electrode busses, the FET gate, and the top plate of the elemental storage capacitor; and the deposition of the silicon dioxide insulation layer that separates the overlying reflective electrode from the underlying circuitry. The traditional chemical vapor deposition (CVD) process used for these materials calls for placing the wafers face up in a carrier (boat) and exposing them to the appropriate hot gasses. The difficulty with this approach is that the desired material is deposited on the walls of the chamber as well as on the wafers, and the chamber must be cleaned prior to each run to avoid particulate matter falling onto the wafer surface. To eliminate this problem, vacuum chemical vapor deposition procedures have been adopted throughout. When there is a partial vacuum, the wafers can be placed vertically in the chamber, and the probability of a particle adhering to a surface is significantly reduced.

4. REFLECTIVE ELECTRODE FABRICATION

For selecting a material to be deposited as the reflective electrode, the handbook optical reflectivity data is only one of several factors to be considered. It must also be: (1) electro-chemically compatible with the liquid crystal material under dc excitation, (2) easily etchable into the ten mil square pattern used to define the individual picture elements, (3) capable of being deposited in a manner that is compatible with the circuits formed on the underlying silicon substrate, and it must also have (4) good adhesion to the underlying layer of silicon dioxide and (5) a bright rather than dull finish without buffing.

Initially, chromium was selected on the basis of experimental measurements because it was found to have the highest reflectivity of the materials that otherwise qualified. Aluminum was ruled out because of its bad electrochemical reactions in a dc driven liquid crystal display. Rhodium was first eliminated on the basis of cost (per ounce it sells for more than platinum) and later because it was very difficult to etch. Silver, too, was initially ruled out; it would not directly adhere to the surface, and its reflectivity was easily degraded by tarnishing. Subsequently, a three-layer metalization scheme was found which provides good mechanical adherence between the final silver layer and the surface of the silicon device, and silver was substituted as the reflective metal.

The silver must be deposited in a high vacuum evaporator if it is to have a bright surface finish; the handling procedures must prevent mechanical abrasion as its soft surface is easily scratched; and care must be exercised to assure that nothing containing or coated with sulphur is placed in the dry nitrogen container in which the unassembled displays are stored. Wafers with a good silver electrode structure have a reflectivity which is 40 percent greater than chromium, and the optical density (D=4) of the metallic layer is sufficient to block the light from entering the underlying circuits.

5. TESTING

Electrical testing of the semiconductor wafers was performed at the half-way point and again upon completion of the wafer processing cycle. These testing procedures used a programmable computerized test station consisting of an automated step and repeat probe station, programmable power supplies, data-bus compatible digital meters, and a Varian mini-computer controller. This equipment was used to measure and tabulate the resistance characteristics of each row (gate) and column (drain) electrode bus. The data obtained provided an indication of the number of shorts or opens which could cause a line defect. If the defect was a short, the machine was programmed to examine and classify the shape of the voltage breakdown curve so as to differentiate between a short to a p+ diffusion, the n-substrate, or a polysilicon resistor short. The machine also compiled and printed out summaries of the test results in a format that permitted the process engineer to rapidly assess the situation. Table 4 shows an example of the detailed data available while Table 5 illustrates a computer prepared overview. This data proved very useful in detecting processing difficulties and establishing wafer quality; excellent quality wafers were provided special handling for the remainder of the processing sequence while poor quality wafers were diverted for experiments where the quality was less important.

Testing of the arrays was not restricted to probing a single line at a time. The special 354-pin probe card shown in Figure 13 was used to permit the evaluation of defect level without the need to complete the normal assembly sequence. To test a wafer: (1) A drop of liquid crystal material was placed in the center of the array and a transparent conductor coated cover glass was lowered onto the array; (2) The probe card was positioned so as to make contact to the 354 pads on the wafer; and (3) An electronics circuit box that provided drive signals for the appropriate rows and columns was connected to the probe card. The processing of a wafer was, tested in this manner, could be continued provided it was specially cleaned to remove all remnants of the liquid crystal material. Most of the wafers processed for the I-HUD program were tested in this manner.

TABLE 4. EXAMPLE OF DETAILED TEST DATA

LINE 1	-000.7420E-6	CURRENT THRU SUBSTRATE	LINE 51	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 2	-000.7370E-6	CURRENT THRU SUBSTRATE	LINE 52	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 3	000.6550E-6	CURRENT THRU SUBSTRATE	LINE 53	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 4	000.1310E-6	CURRENT THRU SUBSTRATE	LINE 54	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 5	000.1820E-6	CURRENT THRU SUBSTRATE	LINE 55	000.0100E-6	CURRENT THRU SUBSTRATE
LINE 6	000.1770E-6	CURRENT THRU SUBSTRATE	LINE 56	000.1610E-6	CURRENT THRU SUBSTRATE
LINE 7	000.1630E-6	CURRENT THRU SUBSTRATE	LINE 57	000.1600E-6	CURRENT THRU SUBSTRATE
LINE 8	000.3400E-6	CURRENT THRU SUBSTRATE	LINE 58	000.1530E-6	CURRENT THRU SUBSTRATE
LINE 9	000.1740E-6	CURRENT THRU SUBSTRATE	LINE 59	000.1540E-6	CURRENT THRU SUBSTRATE
LINE 10	000.1690E-6	CURRENT THRU SUBSTRATE	LINE 60	000.1540E-6	CURRENT THRU SUBSTRATE
LINE 11	000.1640E-6	CURRENT THRU SUBSTRATE	LINE 61	000.1610E-6	CURRENT THRU SUBSTRATE
LINE 12	000.1570E-6	CURRENT THRU SUBSTRATE	LINE 62	000.1470E-6	CURRENT THRU SUBSTRATE
LINE 13	000.1530E-6	CURRENT THRU SUBSTRATE	LINE 63	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 14	000.1510E-6	CURRENT THRU SUBSTRATE	LINE 64	000.0090E-6	CURRENT THRU SUBSTRATE
LINE 15	000.1600E-6	CURRENT THRU SUBSTRATE	LINE 65	000.1630E-6	CURRENT THRU SUBSTRATE
LINE 16	000.1600E-6	CURRENT THRU SUBSTRATE	LINE 66	000.1570E-6	CURRENT THRU SUBSTRATE
LINE 17	000.1600E-6	CURRENT THRU SUBSTRATE	LINE 67	000.1440E-6	CURRENT THRU SUBSTRATE
LINE 18	000.1710E-6	CURRENT THRU SUBSTRATE	LINE 68	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 19	000.1590E-6	CURRENT THRU SUBSTRATE	LINE 69	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 20	000.16[illegible]E-6	CURRENT THRU SUBSTRATE	LINE 70	000.0070E-6	CURRENT THRU SUBSTRATE
LINE 21	000.1660E-6	CURRENT THRU SUBSTRATE	LINE 71	000.1490E-6	CURRENT THRU SUBSTRATE
LINE 22	000.1810E-6	CURRENT THRU SUBSTRATE	LINE 72	000.1440E-6	CURRENT THRU SUBSTRATE
LINE 23	000.1650E-6	CURRENT THRU SUBSTRATE	LINE 73	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 24	000.1610E-6	CURRENT THRU SUBSTRATE	LINE 74	000.0080E-6	CURRENT THRU SUBSTRATE
LINE 25	000.1550E-6	CURRENT THRU SUBSTRATE	LINE 75	000.1390E-6	CURRENT THRU SUBSTRATE
LINE 26	000.1690E-6	CURRENT THRU SUBSTRATE	LINE 76	000.0070E-6	CURRENT THRU SUBSTRATE
LINE 27	000.1630E-6	CURRENT THRU SUBSTRATE	LINE 77	000.1370E-6	CURRENT THRU SUBSTRATE
LINE 28	000.1660E-6	CURRENT THRU SUBSTRATE	LINE 78	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 29	000.15[illegible]0E-6	CURRENT THRU SUBSTRATE	LINE 79	000.0080E-6	CURRENT THRU SUBSTRATE
LINE 30	000.1500E-6	CURRENT THRU SUBSTRATE	LINE 80	000.1470E-6	CURRENT THRU SUBSTRATE
LINE 31	000.1690E-6	CURRENT THRU SUBSTRATE	LINE 81	000.1500E-6	CURRENT THRU SUBSTRATE
LINE 32	000.1530E-6	CURRENT THRU SUBSTRATE	LINE 82	000.1570E-6	CURRENT THRU SUBSTRATE
LINE 33	000.0020E-6	CURRENT THRU SUBSTRATE	LINE 83	000.1550E-6	CURRENT THRU SUBSTRATE
LINE 34	000.0020E-6	CURRENT THRU SUBSTRATE	LINE 84	000.1440E-6	CURRENT THRU SUBSTRATE
LINE 35	000.0010E-6	CURRENT THRU SUBSTRATE	LINE 85	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 36	000.0020E-6	CURRENT THRU SUBSTRATE	LINE 86	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 37	000.0030E-6	CURRENT THRU SUBSTRATE	LINE 87	000.0070E-6	CURRENT THRU SUBSTRATE
LINE 38	000.1640E-6	CURRENT THRU SUBSTRATE	LINE 88	000.1500E-6	CURRENT THRU SUBSTRATE
LINE 39	000.1650E-6	CURRENT THRU SUBSTRATE	LINE 89	000.1460E-6	CURRENT THRU SUBSTRATE
LINE 40	000.151[illegible]E-6	CURRENT THRU SUBSTRATE	LINE 90	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 41	000.00[illegible]E-6	CURRENT THRU SUBSTRATE	LINE 91	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 42	000.0020E-6	CURRENT THRU SUBSTRATE	LINE 92	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 43	000.00[illegible]0E-6	CURRENT THRU SUBSTRATE	LINE 93	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 44	000.0030E-6	CURRENT THRU SUBSTRATE	LINE 94	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 45	000.1310E-6	CURRENT THRU SUBSTRATE	LINE 95	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 46	000.1090E-6	CURRENT THRU SUBSTRATE	LINE 96	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 47	000.1610E-6	CURRENT THRU SUBSTRATE	LINE 97	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 48	000.1640E-6	CURRENT THRU SUBSTRATE	LINE 98	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 49	000.1500E-6	CURRENT THRU SUBSTRATE	LINE 99	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 50	000.0020E-6	CURRENT THRU SUBSTRATE	LINE 100	000.0020E-6	CURRENT THRU SUBSTRATE

TABLE 4. CONTINUED

LINE 101	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 102	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 103	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 104	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 105	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 106	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 107	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 108	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 109	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 110	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 111	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 112	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 113	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 114	000.0040E-6	CURRENT THRU SUBSTRATE
LINE 115	000.1220E-6	CURRENT THRU SUBSTRATE
LINE 116	000.1250E-6	CURRENT THRU SUBSTRATE
LINE 117	000.1240E-6	CURRENT THRU SUBSTRATE
LINE 118	000.1320E-6	CURRENT THRU SUBSTRATE
LINE 119	000.1290E-6	CURRENT THRU SUBSTRATE
LINE 120	000.1260E-6	CURRENT THRU SUBSTRATE
LINE 121	000.1220E-6	CURRENT THRU SUBSTRATE
LINE 122	000.1200E-6	CURRENT THRU SUBSTRATE
LINE 123	000.1260E-6	CURRENT THRU SUBSTRATE
LINE 124	000.1260E-6	CURRENT THRU SUBSTRATE
LINE 125	000.1280E-6	CURRENT THRU SUBSTRATE
LINE 126	000.1290E-6	CURRENT THRU SUBSTRATE
LINE 127	000.1260E-6	CURRENT THRU SUBSTRATE
LINE 128	000.1320E-6	CURRENT THRU SUBSTRATE
LINE 129	000.1200E-6	CURRENT THRU SUBSTRATE
LINE 130	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 131	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 132	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 133	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 134	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 135	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 136	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 137	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 138	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 139	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 140	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 141	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 142	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 143	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 144	000.0040E-6	CURRENT THRU SUBSTRATE
LINE 145	000.0900E-6	CURRENT THRU SUBSTRATE
LINE 146	000.0890E-6	CURRENT THRU SUBSTRATE
LINE 147	000.0880E-6	CURRENT THRU SUBSTRATE
LINE 148	000.0920E-6	CURRENT THRU SUBSTRATE
LINE 149	000.0920E-6	CURRENT THRU SUBSTRATE
LINE 150	000.0930E-6	CURRENT THRU SUBSTRATE
LINE 151	000.0910E-6	CURRENT THRU SUBSTRATE
LINE 152	000.0900E-6	CURRENT THRU SUBSTRATE
LINE 153	000.0930E-6	CURRENT THRU SUBSTRATE
LINE 154	000.0920E-6	CURRENT THRU SUBSTRATE
LINE 155	000.0910E-6	CURRENT THRU SUBSTRATE
LINE 156	000.0900E-6	CURRENT THRU SUBSTRATE
LINE 157	000.0920E-6	CURRENT THRU SUBSTRATE
LINE 158	000.0900E-6	CURRENT THRU SUBSTRATE
LINE 159	000.0830E-6	CURRENT THRU SUBSTRATE
LINE 160	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 161	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 162	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 163	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 164	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 165	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 166	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 167	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 168	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 169	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 170	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 171	000.0020E-6	CURRENT THRU SUBSTRATE
LINE 172	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 173	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 174	000.0010E-6	CURRENT THRU SUBSTRATE
LINE 175	000.0020E-6	CURRENT THRU SUBSTRATE

TABLE 5.

COMPUTER PREPARED OVERVIEW OF TEST DATA.

GATE AND DRAIN LINE ELECTRICAL SUMMARY

MXL-25 POLY

WAFER#		SHORTS MICRO-AMPS 1-10	<100	<500	<1000	>1000	CONTINUITY .5-1M	1-20M	OPEN
17	G SUB	0	0	0	0	0	0	0	0
	DIFF	---	---	0	0	0			
	D SUB	0	0	0	1	1	0	0	4

98.3%YIELD

GATES SHORTED TO SUB= 0 OPEN GATES= 0
GATES SHORTED TO DIFF= 0
DRAINS SHORTED TO SUB= 2 OPEN DRAINS= 4

WAFER#		1-10	<100	<500	<1000	>1000	.5-1M	1-20M	OPEN
13	G SUB	0	0	0	0	0	0	0	1
	DIFF	---	---	0	0	0			
	D SUB	0	1	1	0	0	0	0	1

99.1%YIELD

GATES SHORTED TO SUB= 0 OPEN GATES= 1
GATES SHORTED TO DIFF= 0
DRAINS SHORTED TO SUB= 1 OPEN DRAINS= 1

WAFER#		1-10	<100	<500	<1000	>1000	.5-1M	1-20M	OPEN
3	G SUB	0	0	0	0	0	0	0	0
	DIFF	---	---	0	0	0			
	D SUB	0	0	1	1	0	0	0	0

[illegible]9.4%YIELD

GATES SHORTED TO SUB= 0 OPEN GATES= 0
GATES SHORTED TO DIFF= 0
DRAINS SHORTED TO SUB= 2 OPEN DRAINS= 0

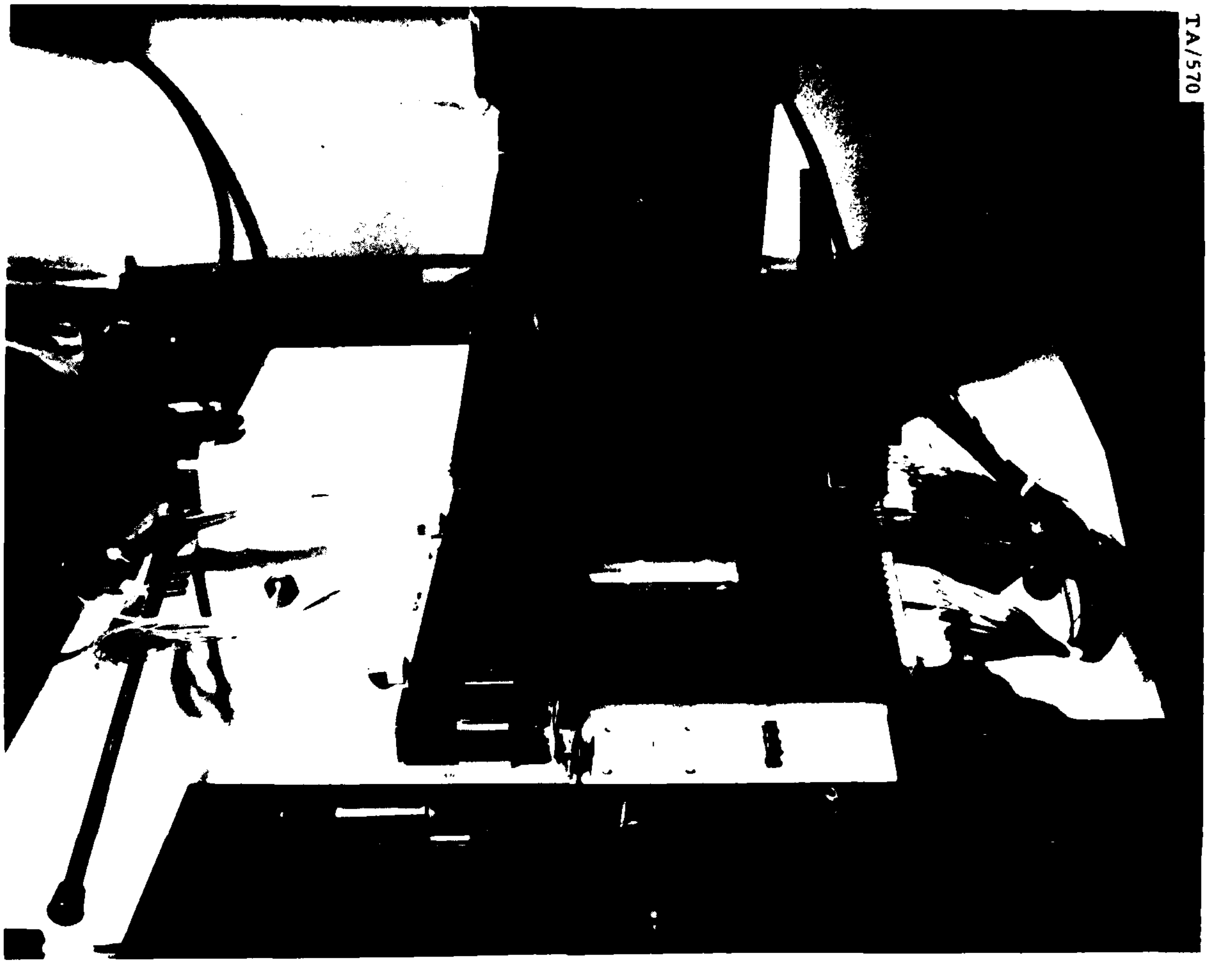

Figure 13. Custom 354-pin probe card manufactured by Probe Rite.

SECTION IV.

QUAD DISPLAY ASSEMBLY

The assembly of a liquid crystal matrix display requires substantially more work than just that needed to produce the silicon wafer. The wafer also must be cut into a square chip, mounted, wire bonded, covered with a conductively coated glass plate, filled and sealed. These processes must also be performed in a manner that is not detrimental to the optical and electro-optical characteristics of the display.

On the I-HUD program, many single displays and several quad displays were fabricated. The assembly procedure for the quad display is similar to that used for the single module displays except that it includes the additional steps needed to arrange the four chips into a physical quad array. The single module displays were fabricated to monitor the progress in the development of the wafer processing procedures and to investigate the suitability of proposed fabrication steps. Of the quad displays fabricated, most were trial assemblies using non-operating components. One of the completed quad displays is shown in Figure 14. A cross section of the unit is shown

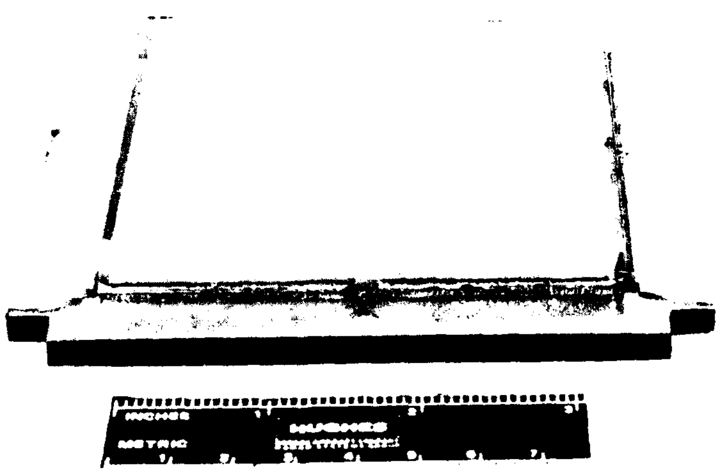

Figure 14. Physical quad liquid crystal matrix display.

in Figure 15. A discussion of the individual fabrication/assembly steps follows. A generic description of the liquid crystal material characteristics will be found in Appendix C to this report.

Sawing. The 1.75-inch square electrode-array modules are cut from the 3-inch diameter silicon wafers by using a precision dicing saw in the manner illustrated in Figure 16. The capability to achieve a straight cutting edge with minimal chipping assures that the junctions between modules in the 2-by-2 mosaic quad array will be nearly indiscernible. Typically, the silicon wafers can be cut to within a 0.0005-inch straightness and chipping specification. The procedure actually employed differed slightly from that illustrated. While mounted faced down with wax onto a specially selected plastic, the wafers were sawed. Mounting in this manner was necessary to protect the delicate silver electrode surface from scratches and contamination during the sawing operation. The plastic was carefully selected after much experimentation for its ability to prevent wafer chipping. Even the method for temporarily mounting the wafers during sawing was the subject of a series of experiments; the materials initially used were found to leave a contaminating residue on the surface that could not be removed by the normal cleaning procedures involving organic and inorganic solvents.

Substrate preparation. A 1/4 th inch thick, 4.852-inch square piece of pyrex glass is used as the mounting substrate. To assure the required flatness, the glass blanks was procured from an optical glass supplier who had ground and polished them to standards normally reserved for lens components. Chromium gold was vacuum deposited on the plates, and they were etched into a pattern. Since the stripes on the circuit plate are used to provide connection to the top of the display, the plates were checked for 100-percent continuity and the absence of shorts. Minor cracks and shorts were eliminated by either spreading out the gold or scratching the surface.

Module Mounting. The square electrode-array modules were mounted in a 2-by-2 quad configuration to the glass substrate to provide physical rigidity and electrical interconnection of the top and bottom of the display. The tooling shown in Figure 17 was specially designed and fabricated to facilitate this operation. The mounting sequence is as follows: (1) The glass printed circuit substrate was clamped to the base in four places. (2) A precut sheet of epoxy coated mylar was positioned on the plate to uniformly deposit the adhesive and to accommodate microscopic surface imperfections. (3) Using the initial

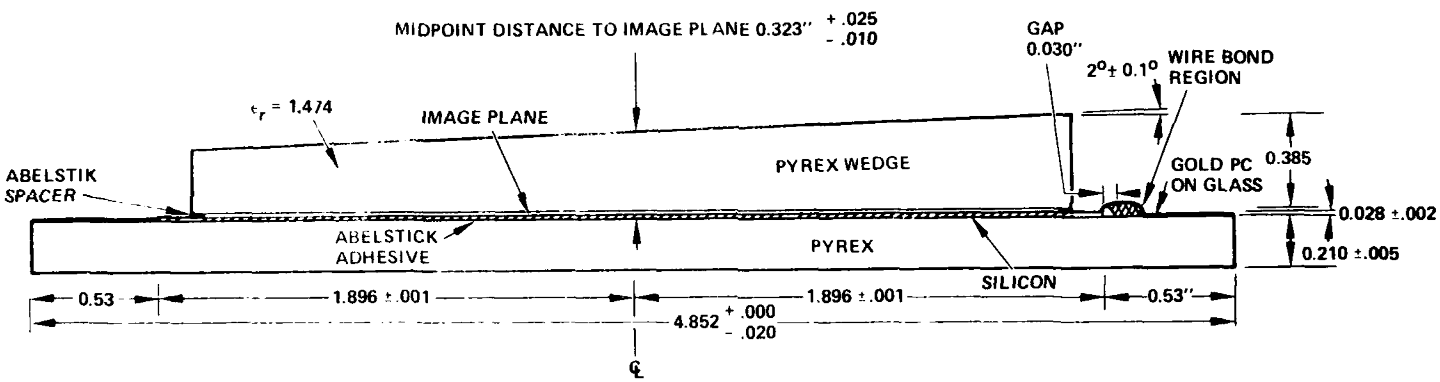

Figure 15. Mechanical layout of physical quad.

quadrant positioning guide and the initial quadrant clamp, the first module was positioned and clamped into place. (4) Using a microscope, the remaining three modules were positioned onto the plate so as to be aligned with the first. (5) The first quadrant clamp was carefully removed, and while the modules were held into place by surface tension, the main pressure plate was placed over the array. (6) The pressure pins on the pressure plates were tightened in order beginning at the center to make sure any wafer bow or curl was eliminated. (7) The entire assembly was placed in an oven to cure the thermal setting epoxy. The entire operation was performed in a clean room area under a filtered air laminar flow bench.

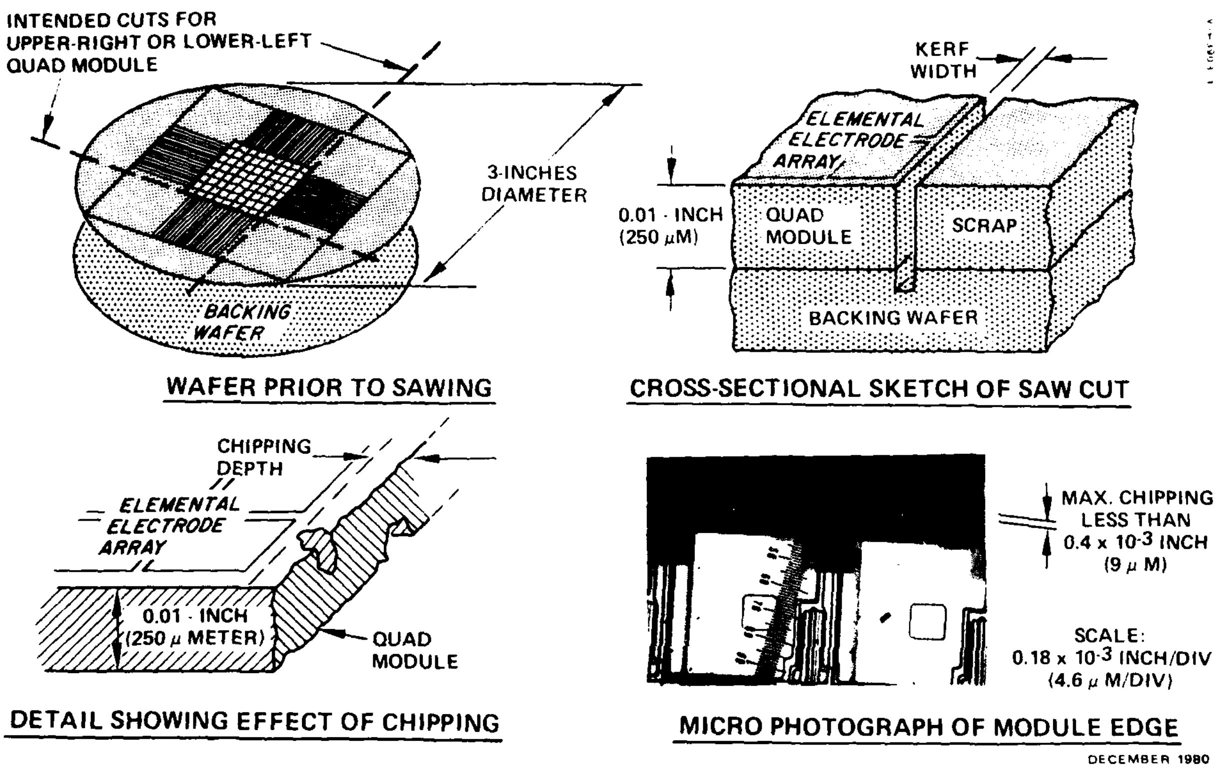

Figure 16. Wafer sawing.

Surface Treatment for Liquid Crystal Alignment. The surface of the modules were texturized in a preferential direction to assure that the liquid crystal material molecules would line-up in the desired crystal-like manner after the display was filled. Uniform liquid crystal material alignment eliminates the blemishes that would otherwise occur at the junction of two differently aligned regions. Alignment was provided by either microscopically scoring the surface using an ion-beam etching procedure or by slant depositing a few atomic layers of silicon dioxide. Both approaches were used successfully; the particular approach used on a given display was primarily related to equipment status and availability.

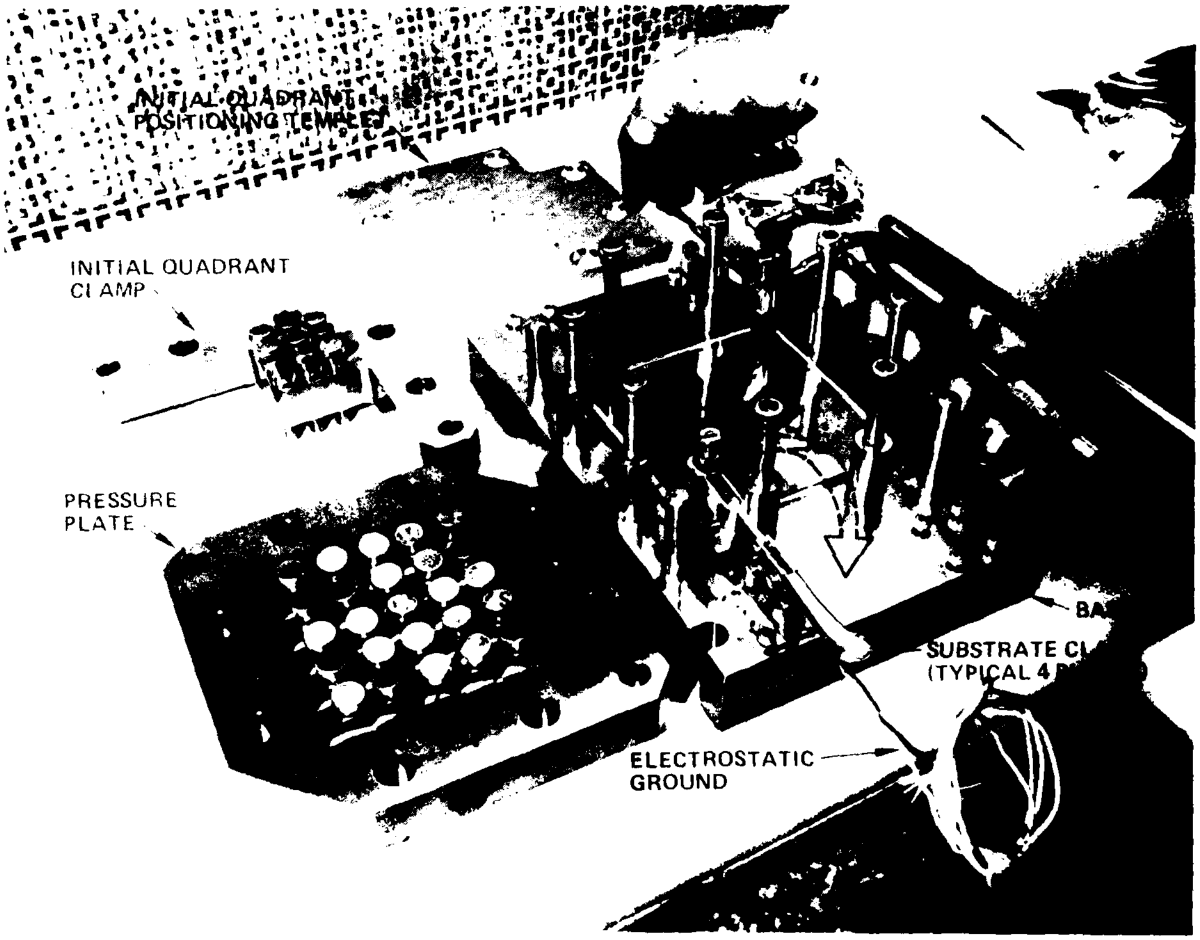

Figure 17. Quad assembly fixture.

Wire bonding. Ultrasonic wirebonding with aluminum wire was used to make the 1408 connections between the modules and the printed circuit wiring on the mounting substrate. Although this operation appears to be a formidable task, it was accomplished by a trained operator in only a few hours. During the wiring bonding operation, the surface of the display was protected from falling particulate matter by a metal shield.

Cover Glass Preparation. The cover was wedge shaped pyrex glass that was coated with a transparent conductor. The cover was wedged shaped so as to direct the first surface reflections away from the aperture hole in the projector. The transparent conductor was indium tin-oxide that had been deposited to a thickness corresponding to one half of a wavelength at 535 nanometers. This minimized the ITO/glass interface reflection shown in Figure 18 which otherwise would have reduced the contrast ratio in the same manner as the unscattered remnant of the incident light. All surfaces of the cover were ground and polished to optical flatness specifications.

Sealing. The chamber to be later filled with liquid crystal material was sealed on all sides with a thermal setting sheet epoxy. Besides physically bonding the cover glass to the module array, the seal prevented the entrance of contaminants during the life of the display. The epoxy was carefully selected to flow at a temperature below that of the epoxy used to previously mount the modules (chips), and to not emit any gasses which might later contaminate the liquid crystal material. Prevention of the later type of contamination also required special handling for the sheet epoxy to prevent it from being contaminated by airborne chemical vapors. Since the epoxy was preformed on the top and bottom surfaces of a mylar sheet, the sealing operation also determined the thickness (typically 0.0005 inch or 12 microns) of the completed cell.

Filling. Prior to assembly, two tiny holes were drilled into diagonal corners of the cover plate for the purpose of filling. The liquid crystal material was forced into and flushed thru the display cell to assure that the dopant concentration was uniform throughout; the dopants adhered to the clean electrode surfaces and the flushing procedure precluded them being concentrated in the area around the fill hole. The fill holes were sealed with a plug of indium and then topped off with a quick setting epoxy.

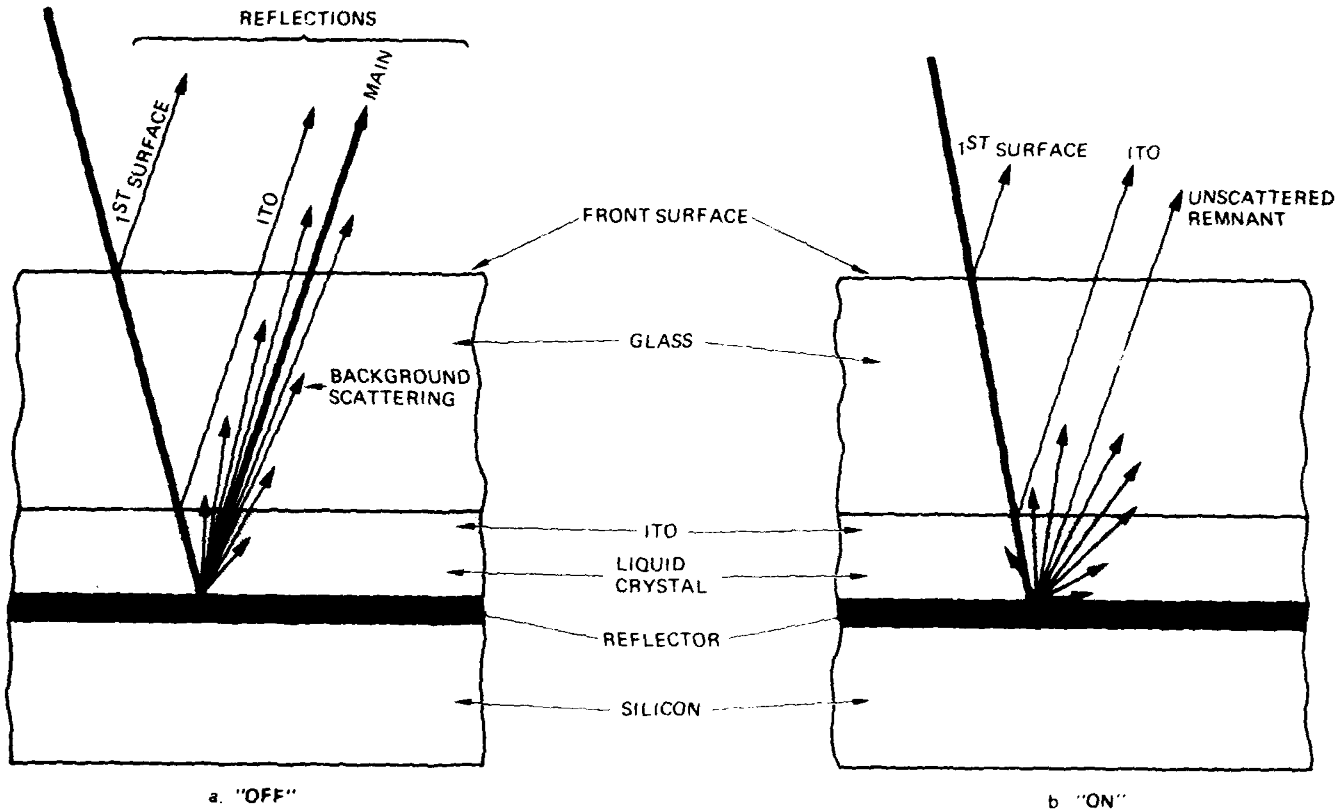

Figure 18. Optical interfaces in the display.

SECTION V.

DISPLAY DRIVERS, INTERFACE CIRCUITS, AND HIGH DENSITY CONNECTORS

1. BACKGROUND

The liquid crystal matrix display requires display drivers, interface circuits, and high density connectors to be directly compatible with a standard television signal.

The signal format for the I-HUD Pilot's Display Unit was initially chosen to be compatible with the output of the DAIS Display Switch Memory Unit (when in the raster output mode), but the signal interface with the I-HUD system was later changed to be either 525-line or 875-line television composite video. Except for the inclusion of an optional element clock, the DAIS signal format is substantially that used for standard noncomposite television interfaces - video, horizontal sync., and vertical sync. The Direct Support Unit (see chapter 10) provides the circuitry necessary to develop these DAIS type signals from the standard composite video waveforms. The input to the direct support unit will therefore accept (without need for adjustment) the signal outputs from most any television tuner, video tape recorder or television camera. Although the signal interface between the Direct Support Unit and the Pilot's Display Unit conforms with the DAIS standards, it is not directly accessible in the I-HUD system; connection is more typically made through the Direct Support Unit.

The circuits packaged in the Pilot's Display Unit with the Liquid Crystal Matrix Display Unit were the display drivers and the interface circuits. A block diagram of these circuits is shown in Figure 19. The form and partitioning of these circuit functions resulted from the need to simplify the display connections. The display surface itself required as a minimum 704 connections - 350 for the 350 rows, 350 for the 350 columns, and two each for redundant connections to the substrate and the counter electrode. However, 1058 connections were actually made as the display was assembled from four non-interconnected modules, and the single layer metalization printed circuit substrate (to which the display modules were mounted) could only connect between two sides of the display. During, a prior program it was found that printed circuit kapton cabling could be used advantageously as a high density connector medium. In the I-HUD system, connection to the display surface was made by pressing Kapton ribbons with conductive stripes against matching patterns on the display mounting substrate. Two 175 conductor cables were used for the 350 rows fed from the left, two 175 conductor cables

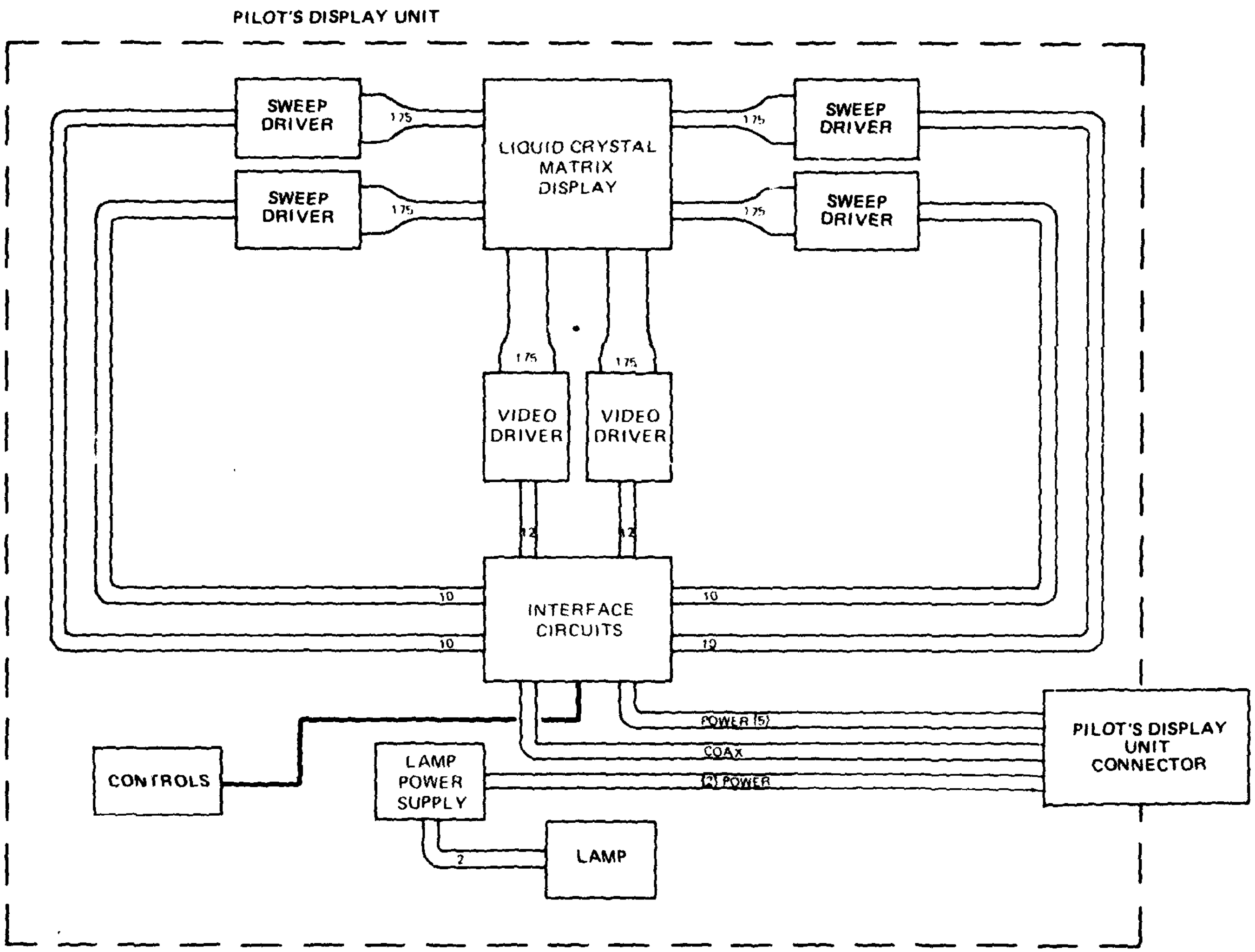

Figure 19. Display driver and interface electronics.

were used for the 350 rows fed from the right, and two more 175 conductor cables were used for the 350 columns with the top and the bottoms being interconnected using the wiring on the printed circuit substrate.

To compactly package the circuitry required to drive all of these rows and columns, custom LSI circuits and printed circuit boards were fabricated. Thirty-five row drivers were placed in a single LSI circuit package, and five of these row drivers were placed on a single printed circuit board, thus 175 rows could be driven by a single board of electronics with its associated high density kapton based printed circuit cable. The column drivers were more complex, and only 22 column drivers would fit in each LSI circuit package. Moreover, their larger package size precluded more than four being mounted to each printed circuit board, and thus each group of 175 columns was driven by two cards of electronics connected to the display surface through a single kapton based printed circuit cable.

To minimize the risk associated with designing and fabricating the custom LSI circuits, those functions whose exclusion would not add to the number of pin-outs were not incorporated into the LSI circuits chips. Therefore, the Pilot's Display Unit contains a card of interface circuits whose function is to generate the signals required by the custom LSI drivers from the DAIS style interface signals. The functions performed by the two interface circuit cards include manipulation of the timing and control signals, providing differential line receivers, buffering of the video signal, and strobing the power to the sweep drive circuits.

The sweep power strobe was added to reduce the power consumption of the row (sweep) LSI circuit drivers when it became apparent that the heat being dissipated within the Pilot's Display Unit potentially represented a thermal problem. The sweep power strobe circuits control the power to the amplifier stages in each group of sweep LSI circuit (row) drivers. As the amplifier stage consumes all of the power, considerable savings were achieved by applying it only to the group having to generate an enable (row activation) pulse during the corresponding time interval. Since there were ten sweep LSI driver chips for each side of the display) this approach cut the power consumption of this group of circuits by nearly 90 percent.

The clock signals provided to the video LSI (column) drivers must have very fast rise and fall times for the video to be sampled precisely. Therefore, on each of the four video cards there are two dual high speed clock driver chips as shown in Figure 20.

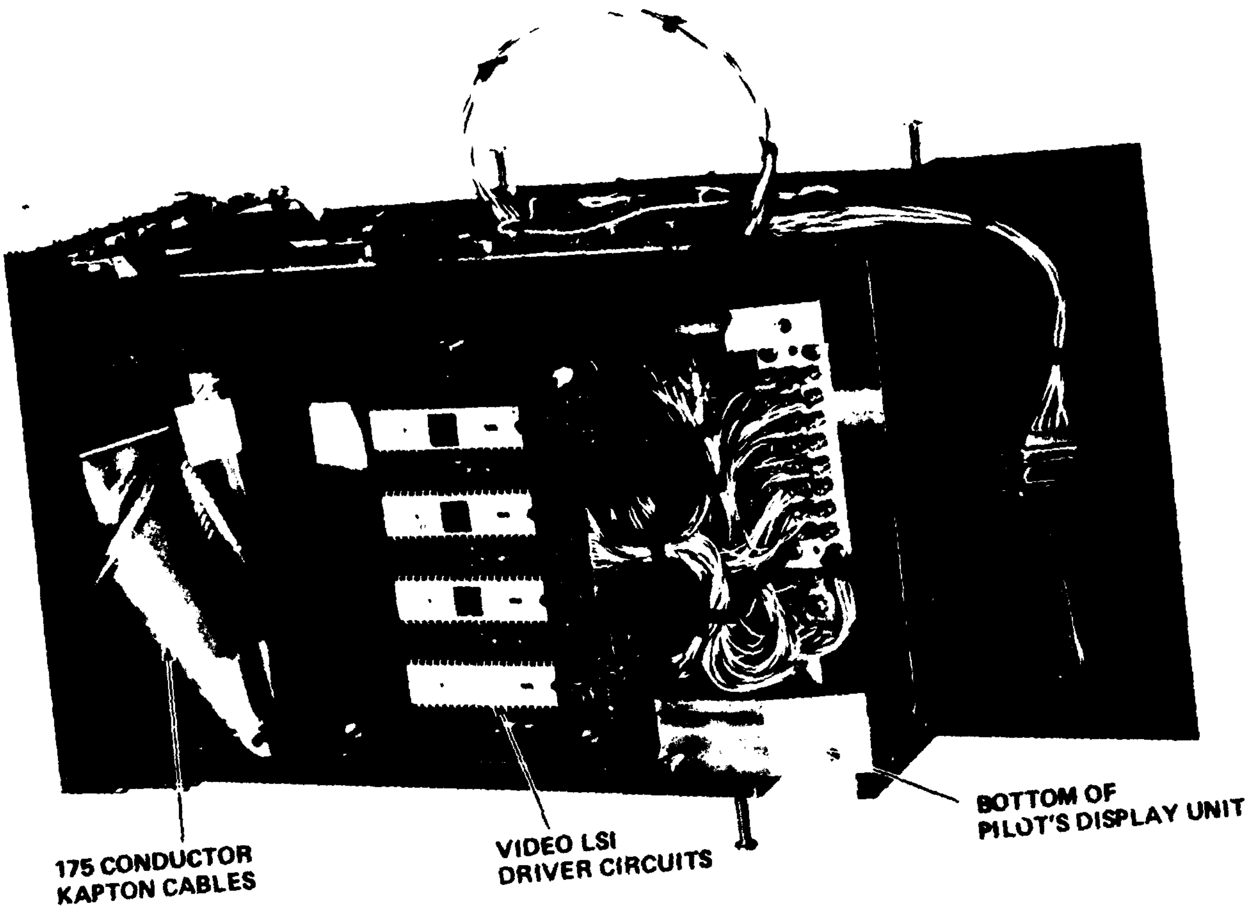

Figure 20. Video driver in I-HUD chassis.

2. VIDEO AND SWEEP TIMING

The Integrated HUD System was designed to operate from raster television formatted signals conforming to either the 525-line or 875-line standards. Since the 350 by 350 picture element format of the liquid crystal matrix display used in the I-HUD system does not match either of these standards, line for line, a portion of the picture information is sacrificed to eliminate the need for a scan converter. The format of the display is set by the timing of the synchronization signals generated by the Direct Support Unit (part of the Test Support Equipment), but it is discussed here as it determines the performance requirements on the LSI driver circuits.

525-line format. The basic timing relationships for a standard 525-line, 60/30 field/frame television signal are shown in Figure 21. Only the upper 350 by 350 picture element area of the 480 by 640 picture element scene is displayed, and the timing is adjusted to preserve the

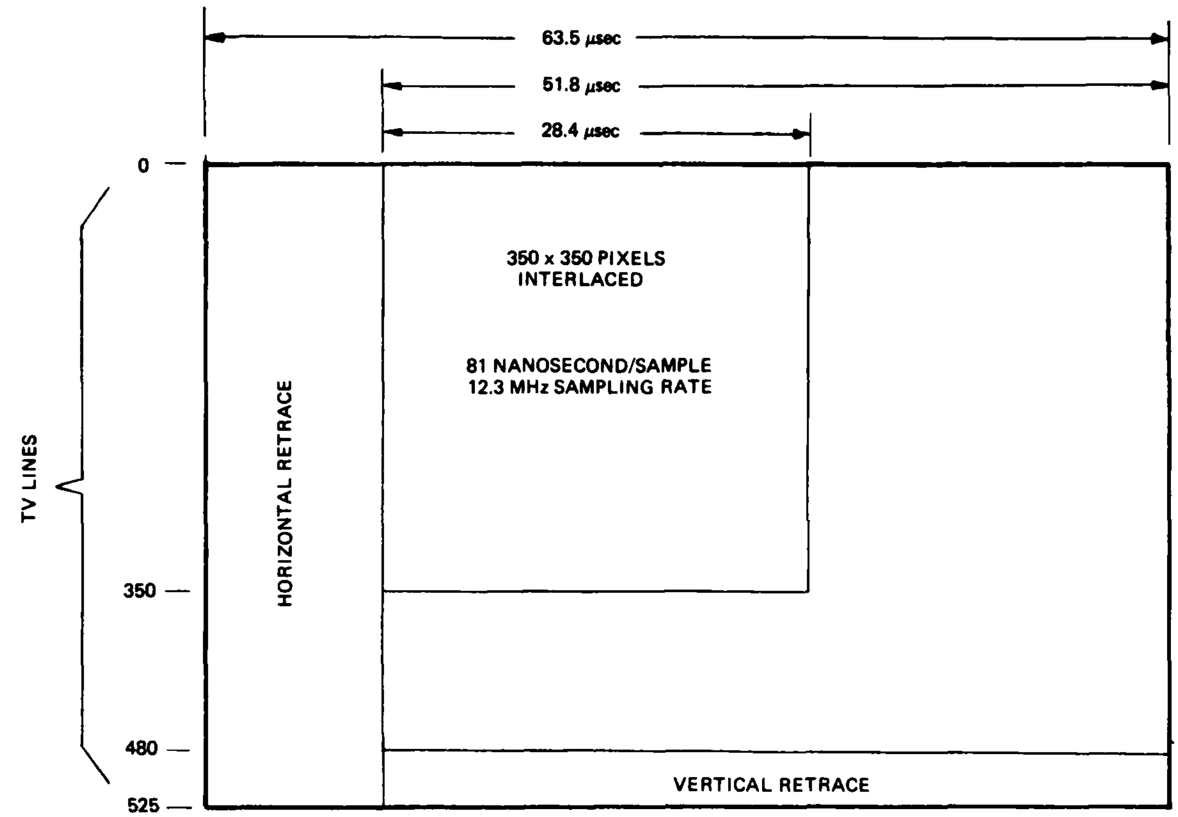

Figure 21. Video sampling for 525-line TV.

geometric fidelity of the image. The horizontal sweep rate is 15,750 hz (30 x 525), and odd/even line vertical interlace is achieved by double pulsing the sweep shift registers during each horizontal retrace interval. These requirements determined that the gate electrode bus lines propagate the row enable pulse in a period of time that was short compared with 63 usec., and the sweep (row) drivers be able to step by two in a period of time short compared with the 13 microsecond horizontal retrace interval. The horizontal video sampling rate is 12.3 Mhz, and 350 samples are taken during a 28.4 micro second portion of the 52 micro second long active line time. A horizontal sampling rate of 12.3 Mhz is equivalent to an 81 nano-second sampling window. The 12.3 Mhz element (sampling) clock, the vertical sync., and the horizontal sync. are phase locked together to prevent moving moire patterns.

875-line format. The basic timing relationships for a square array is shown in Figure 22. The upper 700 by 700 picture element area of the 800 by 1066 picture element scene is merged into a 350 by 350 picture element picture by overwriting the odd and even fields of data into the same picture elements. The horizontal sweep rate is 26250 hz (875 x 30), and the sweep shift registers are pulsed once every 38.1 micro-seconds to ignore the vertical interlace. The horizontal video sampling rate is 12.3 Mhz, so 350 samples are taken during the 28.4 micro-second portion of the active line time. When the input data is formatted with a 3:4 aspect ratio, this timing introduces geometric distortion, which is compensated in the I-HUD system by the Geometric Correction Unit (part of the Test Support Equipment). The 12.3 Mhz element clock, vertical sync., and horizontal sync. generator must provide signals that are

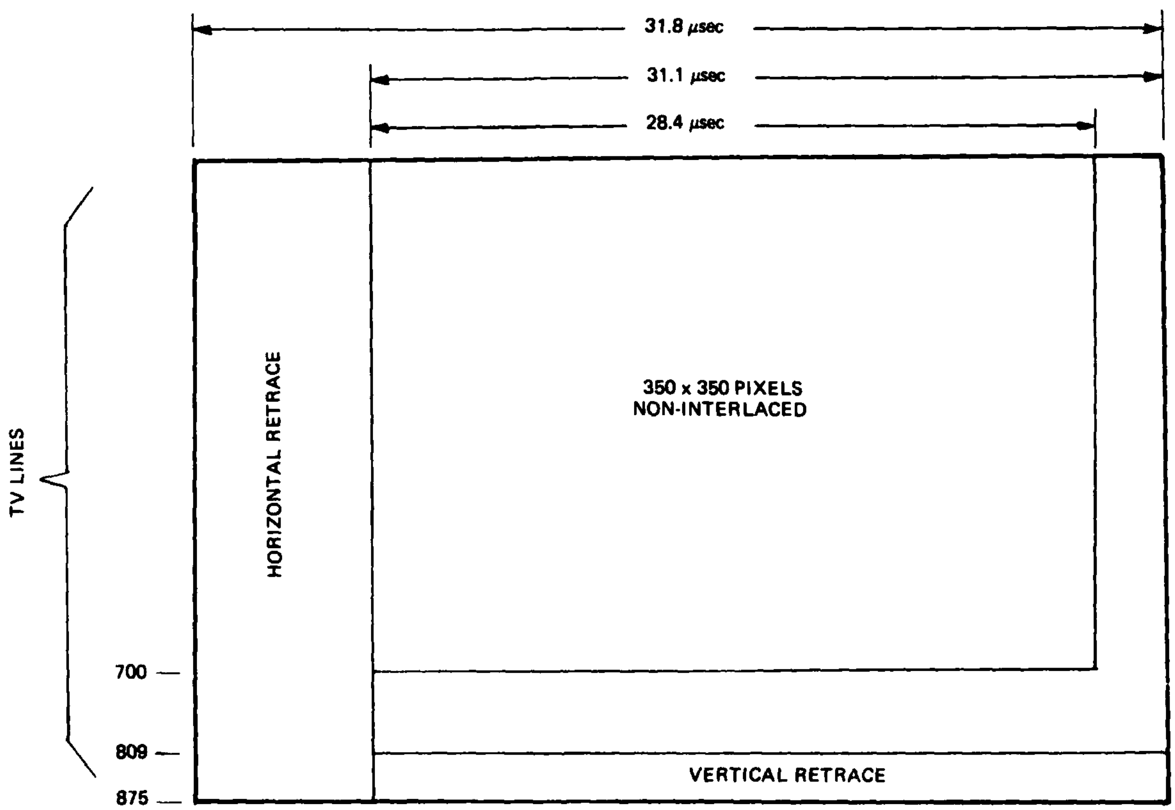

Figure 22. Video sampling for 875-line TV.

phase locked together to prevent moving moire patterns.

3. CUSTOM LSI VIDEO CHIP

The custom LSI circuit chip design can be divided into three functional areas, the shift register, the data storage, and the line drivers. The shift register serves to propagate an enable signal such that the video samples for each column of the display are taken at sequential time intervals. The sampled data is stored in two banks of data bins; one accumulates the new line while the other one outputs the samples accumulated for the prior line. The line drivers provide impedance matching; their high input impedance prevents the voltage on the data storage capacitors from changing significantly while their low output impedance assures that the column electrode busses (drain lines) respond rapidly to new signals.

A key design feature of these chips is the interlaced sampling sequence. The chips are grouped together in sets of four, and they are driven from a four phase clock such that the first chip takes the first sample, the second chip the second sample, etc., until the fifth sample which is again taken by the first chip. A timing diagram for a given chip is shown in Figure 23, while the output interlacing required for placing all the outputs in sequential order is shown in Figure 24. This approach cuts the required shift register clocking rate by a factor of four.

4. CUSTOM LSI SWEEP CHIP

Sequentially enabling the rows of a matrix display is analogous to the vertical sweep function in a CRT based system. The simplicity of the custom LSI circuit chip designed to implement this function is illustrated in the block diagram shown in Figure 25. Only two functional blocks are required, a shift register and an array of buffer amplifiers. The clocking rate of the shift register is less than 30k hz in all modes making its design simple. The design of the buffer amplifier was more difficult as its output must swing nearly 30 volts. To achieve the requisite voltage swing, low output impedance, and packing density, and single ended output is used with a small pull-up resistor. Since the same P-MOS processing sequence was to be used for the drivers as well as the array for the display, this circuit could not be designed to have all the transistors off except the one powering the line being enabled, so a chip power strobing circuit was provided externally to reduce power dissipation.

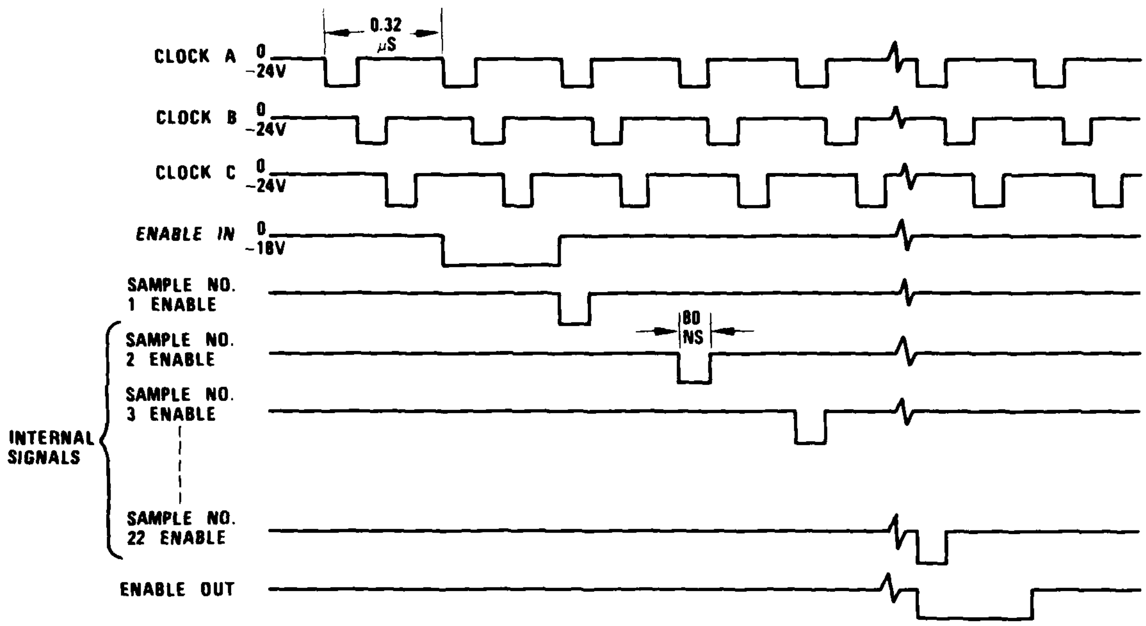

Figure 23. Video driver timing.

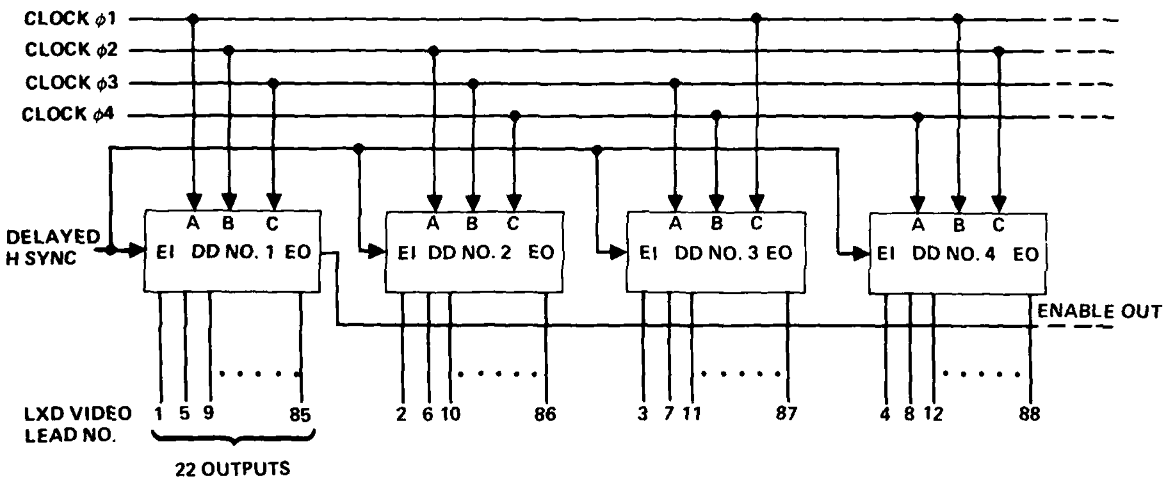

Figure 24. Video driver circuit interlace.

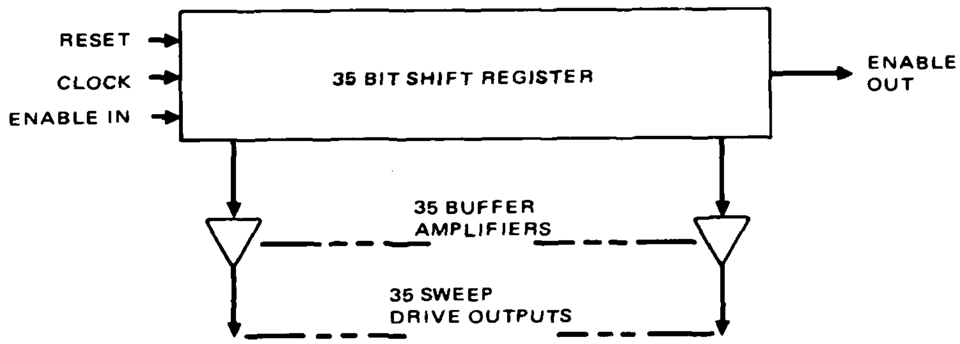

Figure 25. Sweep driver LSI circuit.

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SECTION VI.

ILLUMINATION LAMP

1. BACKGROUND

A special lamp was developed for the I-HUD system. A lamp was required that would be suitable for operation with diffraction optics, a specular mode liquid crystal matrix display projector, and the compact packaging restraints of the F-16 Pilot's Display Unit form factor. The diffraction optics combiner operates only over a very narrow bandwidth to minimize attenuation of the pilot's view of the outside world. Therefore, a narrow band source was needed whose output was in the green portion of the spectrum where the eye is most sensitive. The specular mode projector utilizes a small aperture stop to trap scattered light and enhance display contrast. The luminous area of the light source must be small if most of the light is to pass through the aperture. Thermal considerations associated with the relatively small volume of the Pilot's Display Unit limited lamp power to the [illegible] to 100 watt range. This in turn required a high conversion efficiency from the bulb if adequate brightness was to be obtained. A suitable lamp was obtained by adapting the thallium iodine doped xenon arc lamp developed for underwater search lights to a smaller, lower power package.

2. LAMP CHARACTERISTICS

The lamp (developed by the ILC Corporation for Hughes) is shown in Figure 26. It is a metal halide, short arc lamp whose design is derived from that for a larger 400-watt arc lamp. A metal halide arc lamp provides both high efficiency of light generation and the design latitude to selectively choose wavelength and color balance of the output. Additionally, the arc lamp has potential for long-life operation and immunity to strong mechanical shocks. Halide arc lamps operate by an electric discharge which is passed through an atmosphere of inert gas (xenon) and a metal halide vapor generated by a liquid pool of halides condensed on the cooler regions of the lamp envelope. The intense radiation resulting from such a discharge occurs mainly at the atomic lines characteristic of the metals used.

The light output of the thallium iodide lamp is well matched to the bandwidth requirements of diffraction optics element as shown in Figure 27. The small 0.100 inch separation between the electrodes is equal to the aperture hole diameter thus assuring a high efficiency specular projector. Its low wattage and high conversion efficiency made it a very good choice considering the packaging restraints. As shown in Figure 28, conversion

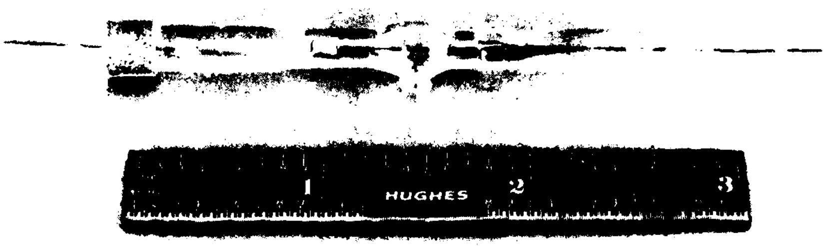

Figure 26. 50 Watt thallium iodide arc lamp.

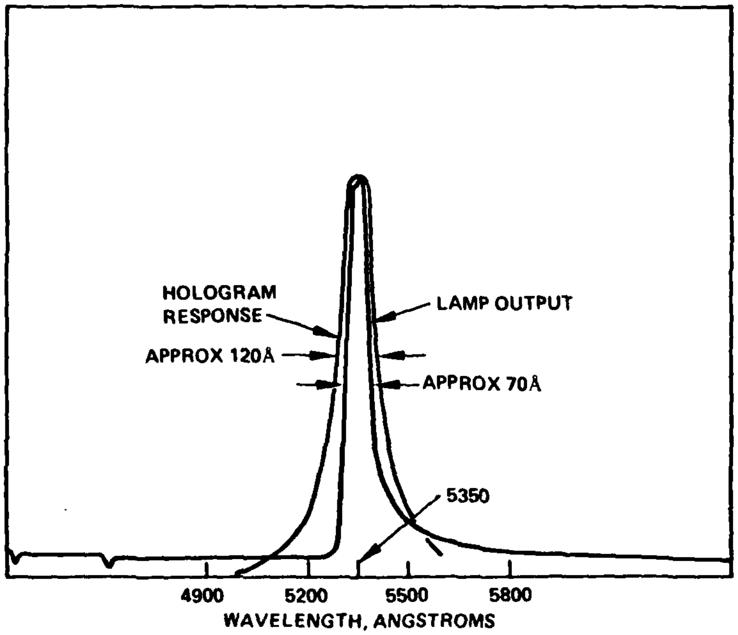

Figure 27. Hologram-lamp spectral overlap.

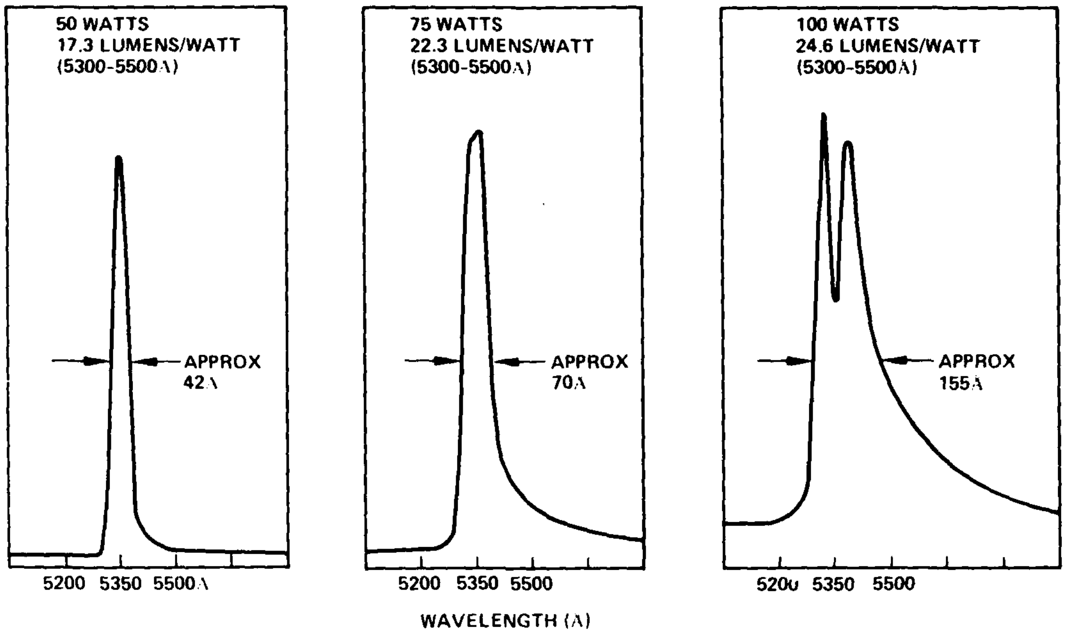

Figure 28. Lamp output versus power.

efficiency is maintained at low power levels and is still over 17 lumens per watt with only 50 watt input power. The high efficiency of this lamp is compared with incandescent light sources; comparable tungsten lamps typically provide only 15 lumens/watt, and their light output is spread across the whole visble spectrum.

The lamp radiates light with nearly a donut shaped radiation pattern as shown in Figure 29 as a result of the shadows caused by the cathode and anode. However, the light distribution across the arc was found to be closer to the characteristic shown in Figure 30 than the initially assumed 0.1-inch diameter sun ball. Moreover, the position of the most intense point does wander, and it is not green in color. The manufacturer of the lamp indicates that arc positional stability can be improved by optimizing the shape of the electrodes, and a new doping procedure has been developed which yields a greener arc hot spot simultaneously with a slight increase in the conversion efficiency.

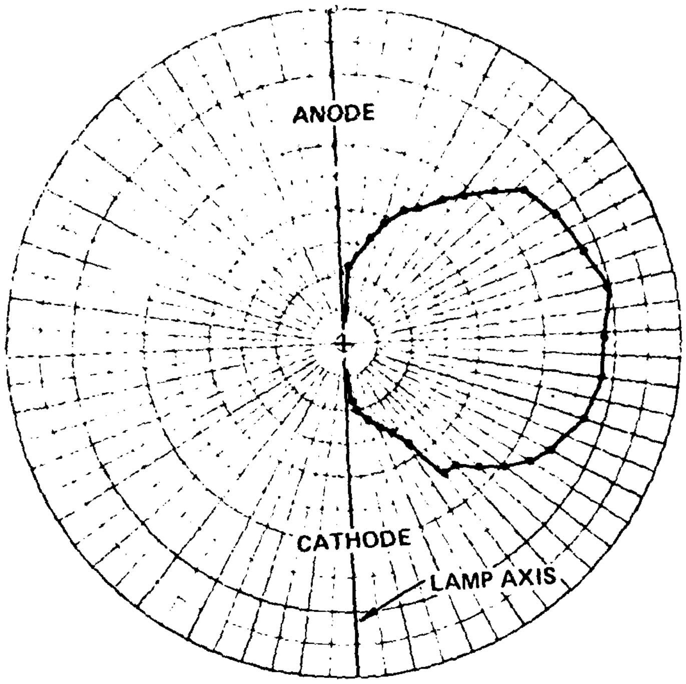

Figure 29. Lamp polar radiation distribution.

3. I-HUD INSTALLATION

The thallium-iodide doped xenon arc lamp is installed above the elliptical reflector as shown in Figure 31. Forced air cooling is provided by two 400 hz fans. Below the lamp is a filter to shield the ultraviolet (UV) light sensitive liquid crystal material from the strong UV output of the lamp, (see Figure 32), and to minimize heating of the display. The filter was fabricated by depositing a dielectric "hot mirror" coating on top of the Schott glass that had previously been ground into the required spherical shape. The hot mirror coating reflects the infrared (IR) back into the lamp. The spectral characteristics of the lamp filters are shown in Figure 33.

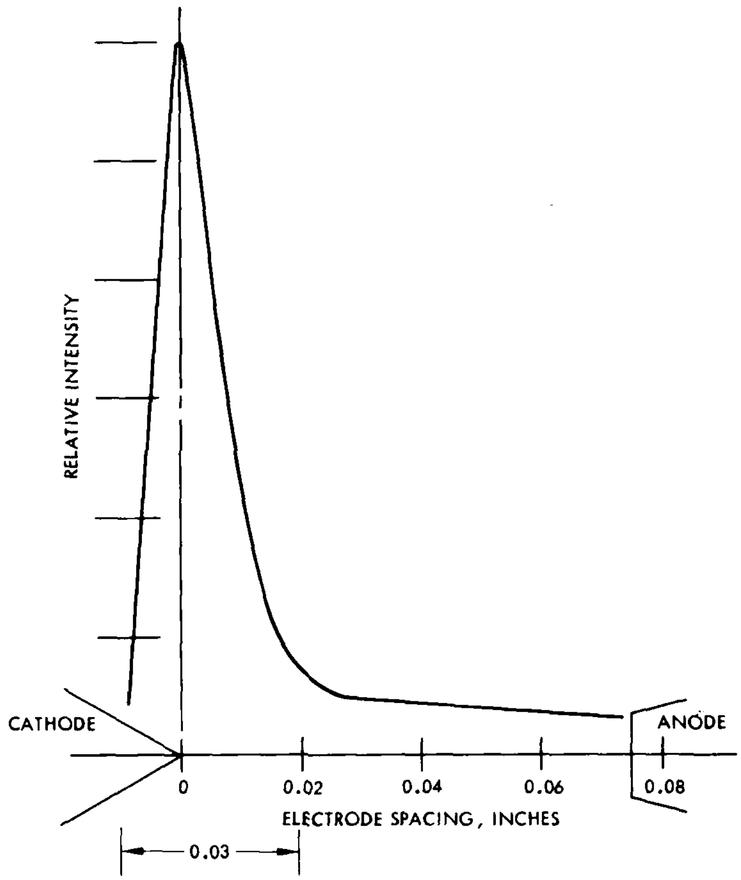

Figure 30. Arc intensity distribution.

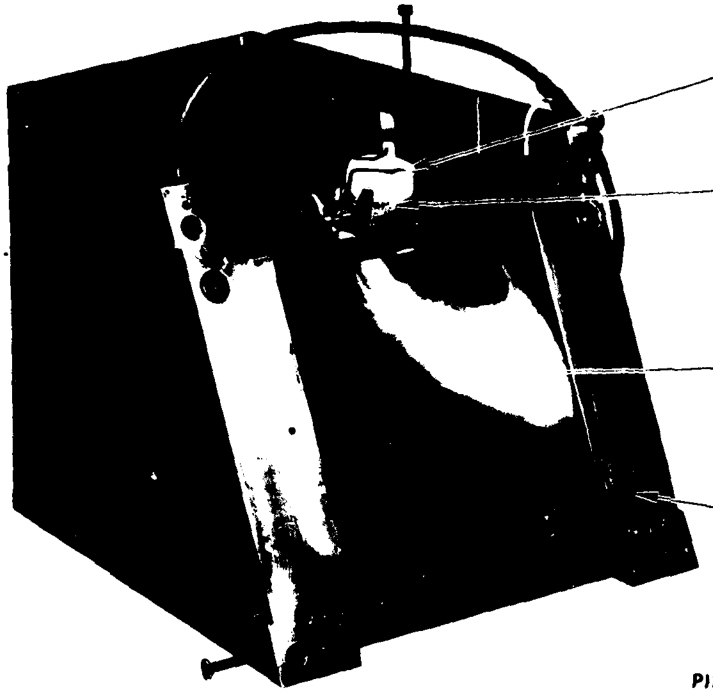

Figure 31. Lamp installation.

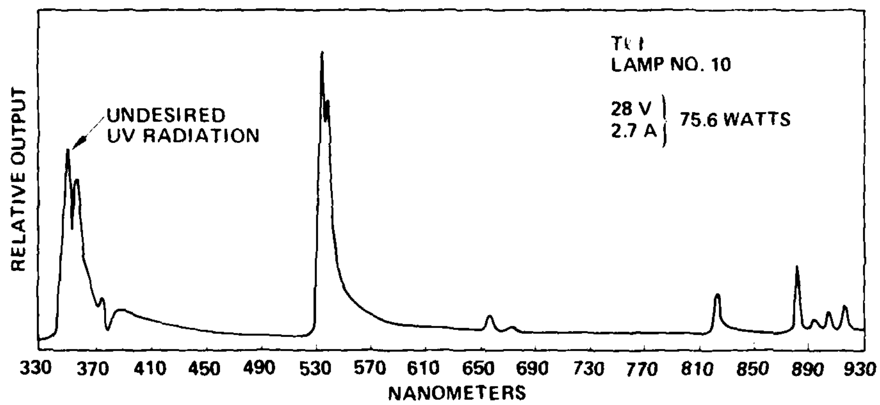

Figure 32. Lamp spectral output.

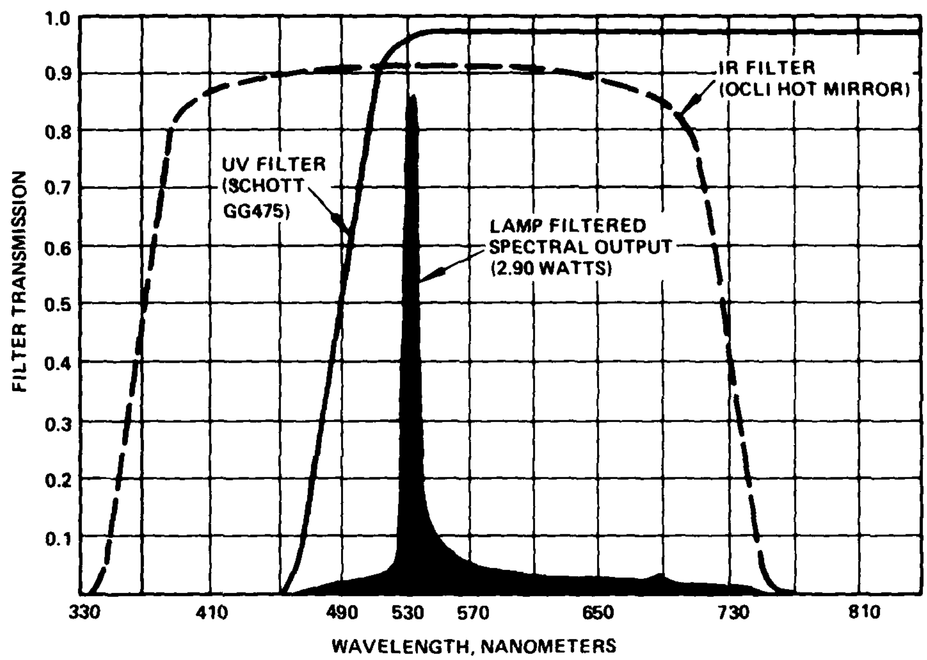

Figure 33. Illumination filter characteristics.

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SECTION VII.

SPECULAR MODE PROJECTOR

The combination of the liquid crystal matrix display, the high intensity lamp, the specular mode projector optics, and the diffusing screen, provide the function normally accomplished by a CRT. In the specular mode projector, the liquid crystal matrix display serves as a light modulator which imparts temporal, spatial, and intensity variations to the light generated by the lamp. A specular mode projector was used because it provides high brightness when the light modulator is a dynamic scattering liquid crystal material. Other approaches which were considered included those for capturing the scattered light or using polarization effects. A projector which captured most of the scattered light (and rejected the specularly reflected light) required low-F/number lenses which are both large and expensive. A projector using polarizers has the disadvantage that more than half the light is lost in the initial polarizer. With low loss optical components the specular mode projector directs most of the light captured from the lamp onto the screen. Moreover, because a specular mode projector approximates a pin-hole source of light, the design and fabrication of the projection lens and diffraction optics diffusing screen are simplified.

1. SPECULAR PROJECTOR OPERATION

The theoretical operating concept of the specular projector is illustrated in Figure 34 which shows a simplified optical schematic. The lamp provides a point light source which is gathered and focused to a point in the center of an aperture. The liquid crystal matrix display is actually a mirror used to fold the optical path at the plane indicated by the dashed line, but it is shown as a transmissive element in order to unfold the optical path. The light reflected off the surface of the liquid crystal matrix display and within the acceptance cone of the aperture is focused by the projection lens onto the screen. In practice, the aperture is proportionately smaller than that shown in Figure 34, and it thus prevents most of the scattered light from reaching the screen. Thus, little light is allowed thru the aperture from those areas of the display where the liquid crystal material is in a state of hydrodynamic turbulence (as a result of being activated by an electrical signal). As the "on" areas appear dark and the "off" areas appear bright, the video signal to the liquid crystal matrix is inverted to provide a normal white on black image at the screen. The limiting brightness efficiency of the projector is primarily determined by: (1) the solid angle subtended at the source by the condensing optics and (2) the size (cross sectional area) of the image of the source at

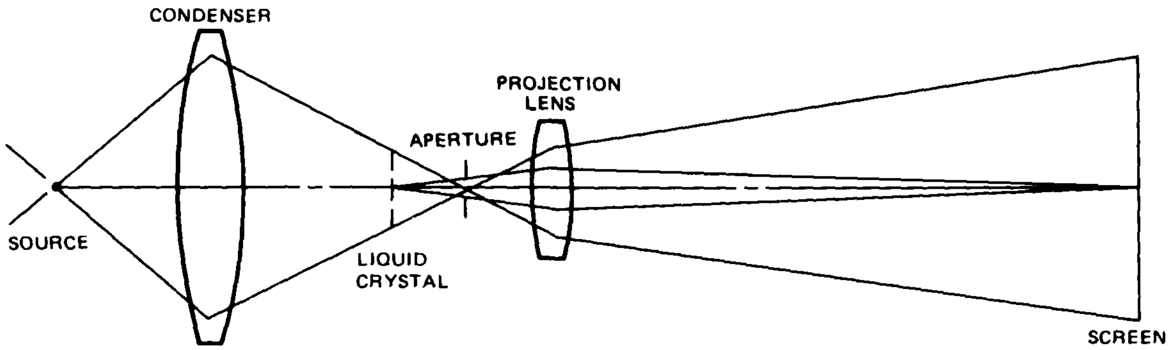

Figure 34. Simplified schematic of specular projector.

the aperture plane relative to the size of the aperture itself. The contrast obtained is inversely proportional to the size of the solid angle subtended at the display surface by the aperture.

The I-HUD system uses an elliptical reflector of revolution as the condensing optics element. This reflector also contains a pinhole aperture. As shown in Figure 35, only a segment of the reflector is used, the lamp is positioned at one of the foci of the reflector. The light from the lamp is focused to a point in the center of the aperture by placing the mirror image of the aperture at the other focus of the ellipse. This was accomplished by placing the liquid crystal display in a plane which was normal to and bisected the imaginary line drawn from the center of the aperture hole to the second focus. As in the previous example the liquid crystal matrix display is actually used to fold the optical path, but the display is shown as a transmissive element to simplify the diagram.

The actual packaging scheme of the I-HUD projector is shown in Figure 36. The screen was tilted slightly to introduce trapezoidal geometric distortion of an opposite nature to that produced by the diffraction optics combiner. In that way the geometric distortion of the system was somewhat reduced. In future systems, the projection lens could be designed as a series of general aspheric elements which would precisely compensate for the geometric distortion subsequently introduced by the off-axis diffraction optics HUD system.

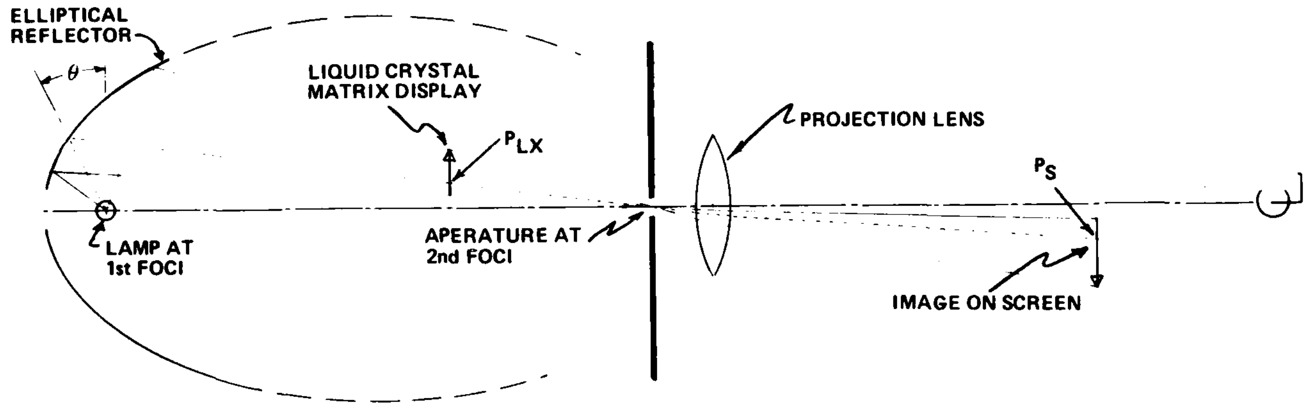

Figure 35. Specular projection with elliptical reflector.

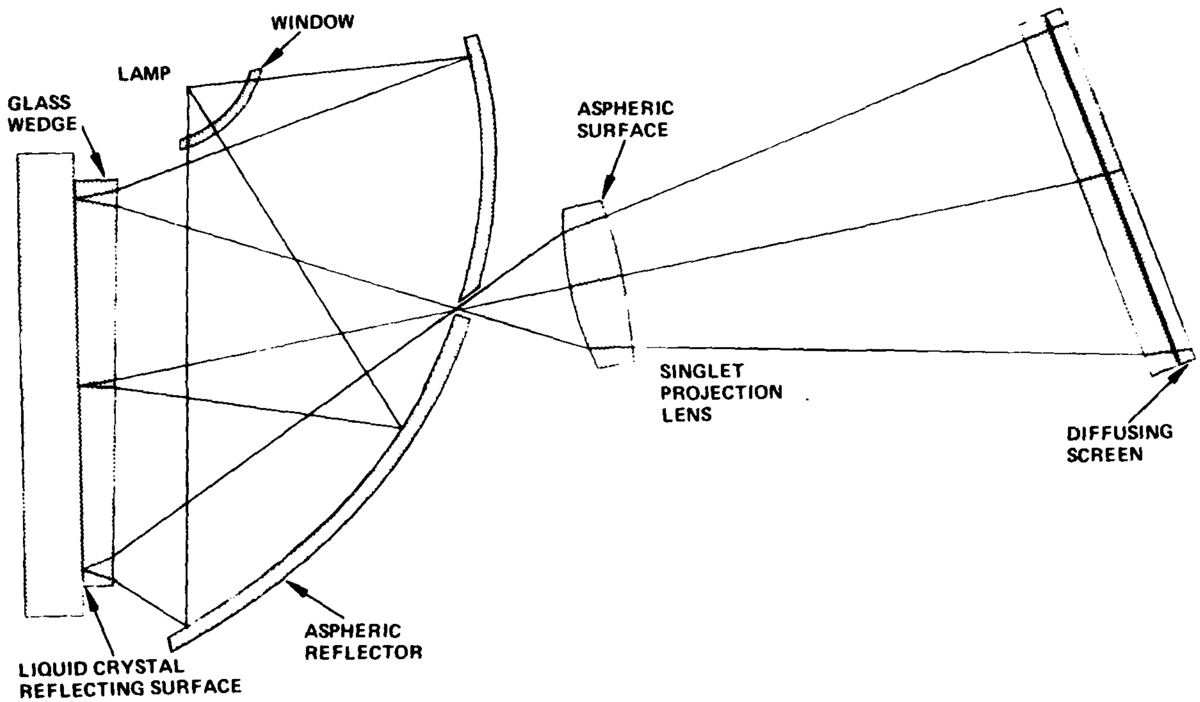

Figure 36. I-HUD system specular projector.

SECTION VIII.

DIFFRACTION OPTICS DIFFUSING SCREEN

A diffraction optics diffusing screen is required in the I-HUD system to achieve a bright, large, and uniformly illuminated exit pupil from which the pilot can see the entire field of view. A diffusing screen is necessary if the efficient specular mode projector and liquid crystal matrix display combination (used to obtain a bright image) is not to limit the size of the system exit pupil. Furthermore, a diffraction optics diffusing screen makes it possible to achieve high screen gain and compact packaging without having the display brightness change significantly with viewer position within the exit pupil of the system.

In the I-HUD system, the screen is placed so that it is illuminated by the specular mode projector whose light has been spatially modulated by the liquid crystal matrix display, and the screen is viewed by the pilot through the HUD optics consisting of the diffraction optics combiner, folding mirror, and relay lens. Without a diffusing screen, the limiting aperture of the optical system becomes the small aperture of the specular mode projector. A diffusing screen makes it possible to have the large exit pupil desired for easy viewing and the small specular mode projector aperture required for high contrast.

Increased screen brightness can be obtained by making use of the fact that the screen need not diffuse light in all directions; it is only necessary that it be diffused into the direction of the relay lens entrance pupil. A screen having directional properties is said to exhibit screen gain, because its brightness in a given direction can be brighter that that of an ideal lambertian diffuser. (An "ideal" lambertian surface appears uniformly bright from all viewing angles.) Brightness gain is not inconsistent with the concept of conservation of energy as the screen is merely concentrating the energy incident on it to one small area instead of spreading it out over a whole hemisphere.

A screen that has gain, diffuses the light incident onto it into a lobe centered about the angle of the incident ray. With high gain screens, this can lead to non-uniform brightness across the field-of-view as shown in Figure 37. An approach for improving this situation uses a Fresnel lens with the high gain screen. The Fresnel lens can usually be selected such that there is no change in brightness across the field of view when the screen is observed from the design eye location as shown in Figure 38. The Fresnel lens also improves the brightness

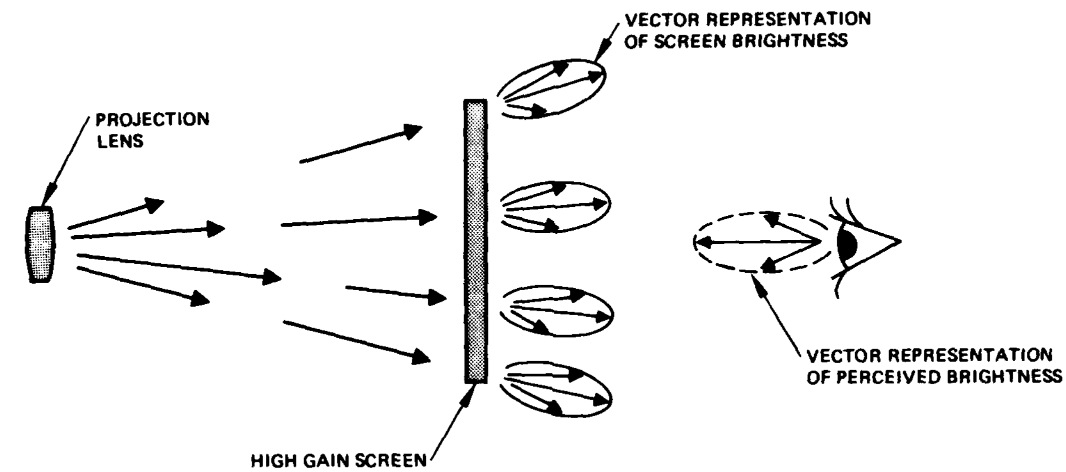

Figure 37. Brightness uniformity with high gain screen.

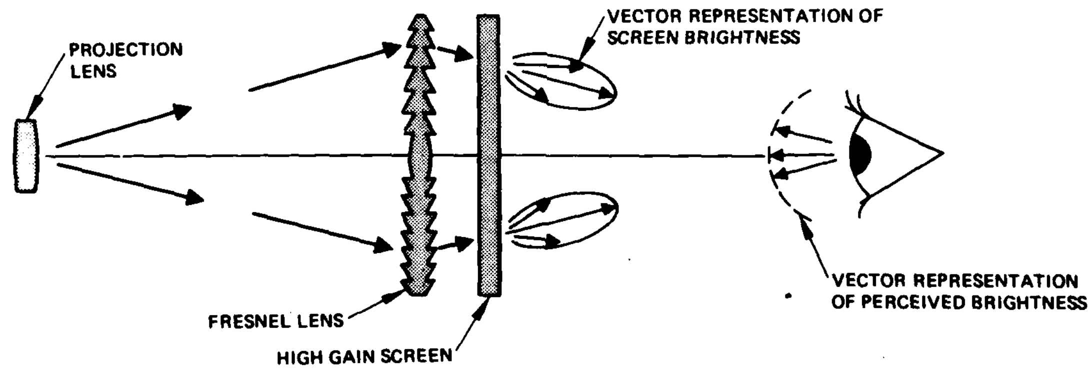

Figure 38. Fresnel lens improves brightness uniformity.

uniformity at other positions in the field of view.

In the integrated HUD it was desirable to use a screen with as high a gain as possible, as the brightness of the symbology in the combiner is directly proportional to screen gain. The physical configuration of the I-HUD, however, placed severe constraints on the choice a diffusing screen. The initial concepts called for the use of a standard Polycoat high gain screen in combination with a Fresnel lens to get an average screen gain of 5, but it later became evident that this combination would not allow an acceptable compromise between screen gain and brightness uniformity. It was decided that a diffraction optics diffusing screen would be designed and fabricated since it would have a greater ability to re-aim and confine the light to a small exit pupil (as shown in Figure 39) than a conventional screen.

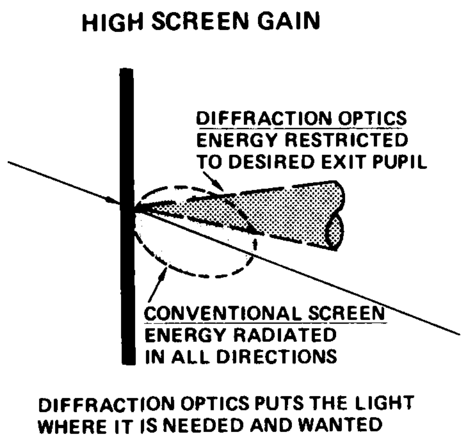

Figure 39. Conventional and diffraction optics screens compared.

Figure 40 shows the screen gain anticipated from a 100-percent efficient diffraction optics diffusing screen optimized for the I-HUD geometry. The data is presented as a function of position on the liquid crystal matrix display (the mirror matrix) to provide a standard positional reference. The gain variations resulted from a design which maximumized gain at all viewing positions.Some non-uniformity was desirable in order to compensate for variations elsewhere in the system. The screen installed in the I-HUD hardware was 15 to 20 percent efficient, and therefore its gain was correspondingly less than if the theoretical maximum efficiency of 80% had been achieved. Even with this far less than ideal performance, the diffraction optics diffusing screen contributed significantly to the high brightness of the I-HUD system. When efficiencies near the projected maximum are realized, very high brightness HUDs will be possible.

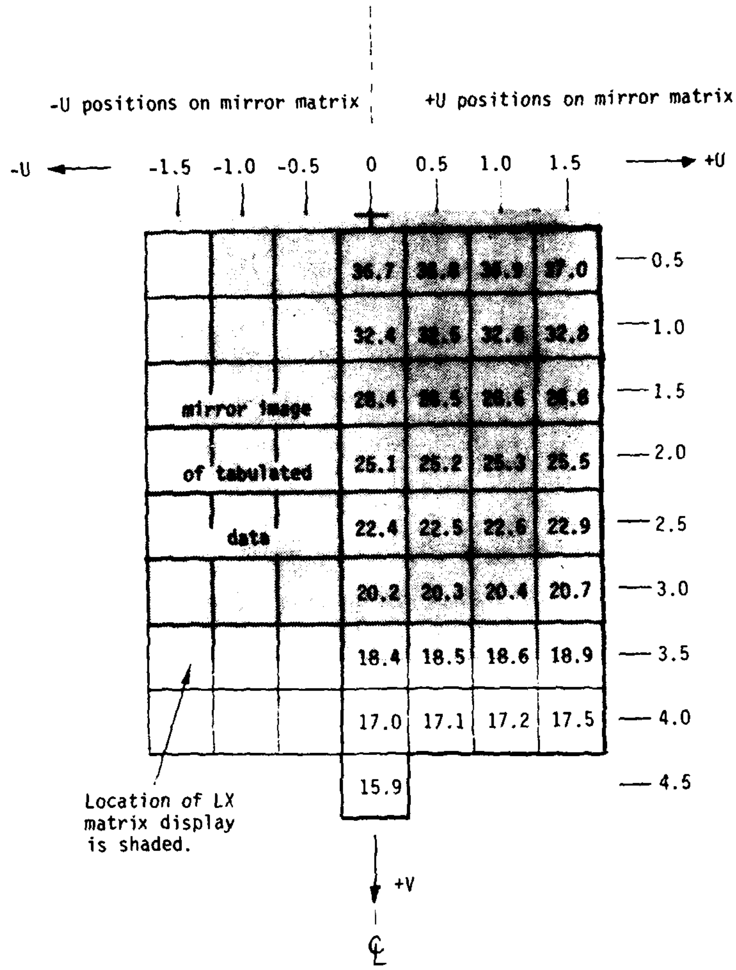

Figure 40. Ideal gain of diffraction optics diffusing screen.

SECTION IX.

HUD OPTICS AND DIFFRACTION OPTICS COMBINER

1. BACKGROUND

The optics for the I-HUD system can be partitioned into two subsystems: (1) the image projector - those components necessary to form an image onto the diffraction optics diffusing screen and the screen itself, and (2) the HUD optical display unit - those components necessary to relay that image into the pilot's field of view in a manner such that it appears at infinity. The HUD optical display unit design is independent from the image projector design; a cathode-ray tube display or a liquid crystal matrix display specular projector may be used, and indeed the HUD optical display unit used for the I-HUD system was modeled after previous CRT based designs.

Diffraction-optics-combiner HUD designs, such as that used for the I-HUD system, have been under development at Hughes for more than ten years. They evolved from early efforts at the Hughes Research Laboratories to design thin film optical elements by recording laser wavefronts on photosensitive film. This technology in turn built on that used for holography and hence the term holographic optical element is sometimes used in connection with diffraction optics elements. An example of what can be achieved with a diffraction-optics-combiner HUD is the unit shown in Figure 41. Built for and flight tested by SRA, a Swedish military electronics company, this HUD provided a 20-degree elevation by 35-degree azimuth field of view while constrained to fit into the cockpit on an existing Viggen aircraft. The I-HUD program did not attempt to provide the same very wide field of view because of the more restrictive packaging contraints associated with the F-16 aircraft. However, the 12-degree elevation by 16-degree azimuth instantaneous field of view of the I-HUD design is still substantially larger than the truncated nine-degree circular field-of-view of the conventional F-16 HUD units.

2. DIFFRACTION OPTICS HUD CONCEPT

The basic elements of a diffraction optics HUD are illustrated in Figure 42. The function of the combiner is to collimate the light from the internal image source so that the imagery appears to the pilot as if it is located at infinity. The folding mirror is used to place the optical components into the space behind the instrument panel the mirror must clear the pilot's ejection path. The relay lens re-images the image source and compensates for the optical abberations introduced by the combiner. The image source can be either a CRT or a flat panel display provided the wavelength of the light it emits (or reflects) is restricted to the narrow band for which the diffraction optics combiner has been designed and optimized.

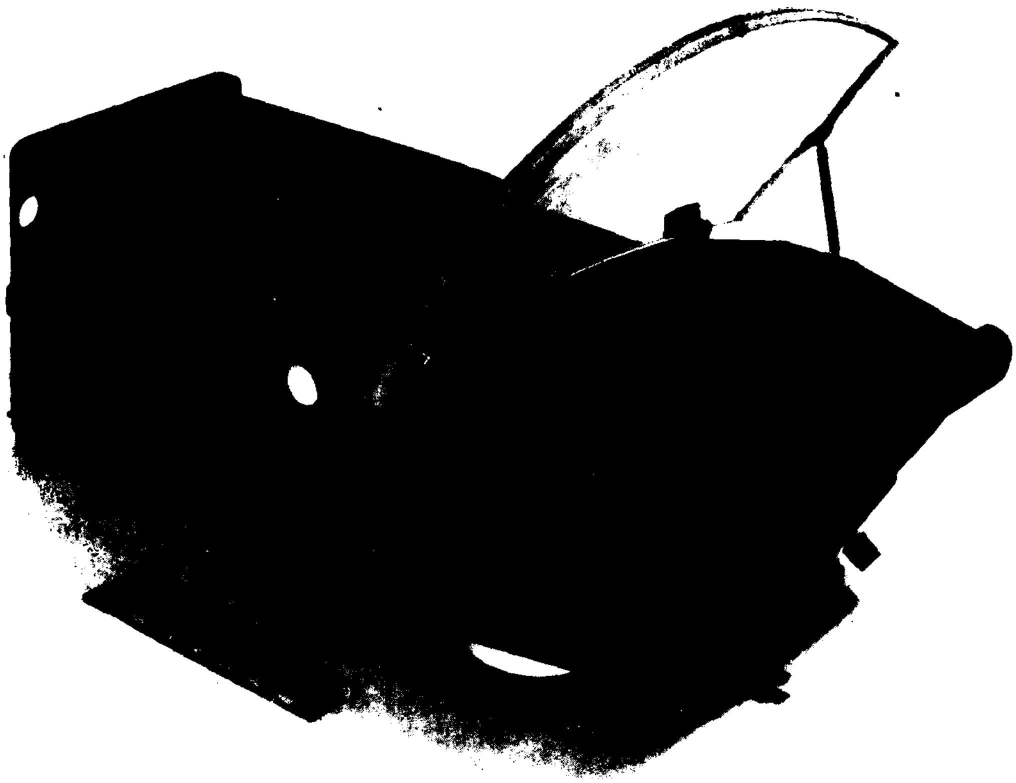

Figure 41. Example of wide field-of-view HUD.

The diffraction optics combiner is used in an off-axis reflective optics configuration to provide increased field-of-view in a restricted volume. This complicates the design of the relay lens. The combiner is equivalent to a section of an aspheric surface of revolution whose axis does not pass thru the combiner. Although the glass substrate is a section of a sphere, the hologram itself functionally assumes the shape of a general aspheric, giving sufficient design flexibility to obtain the needed level of performance.

As the optical properties of a diffraction optics combiner are wavelength sensitive, the system is designed to operate within a narrow band of optical wavelengths. When a CRT is used as an image source, a P-43 phosphor is typically chosen as its

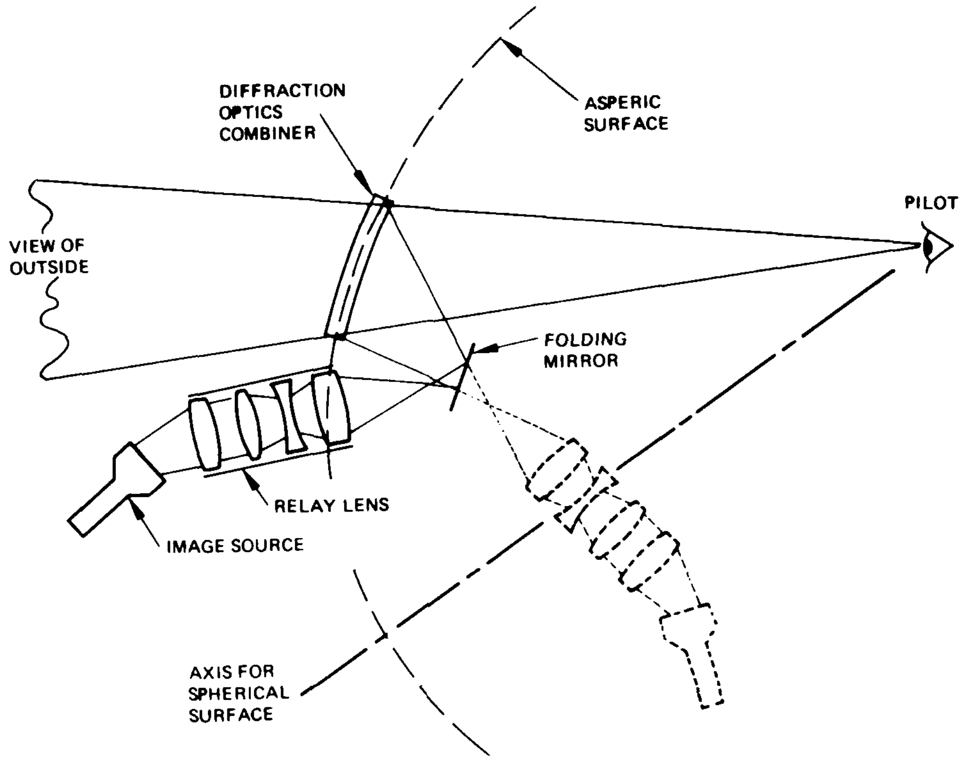

Figure 42. Basic diffraction optics HUD concept.

output is concentrated around 543 nanometers. When a liquid crystal display is used, a narrow band illuminator is provided. The I-HUD system uses a thallium-iodide doped Xenon arc lamp to obtain light concentrated in a narrow band around 535 nanometers. The construction optics used to expose the combiner and the subsequent processing of the combiner was custom designed and fabricated to optimize the efficiency and performance of the combiner at the 535 nanometer wavelength used in the I-HUD system.

3. COMBINER FABRICATION

Unlike a conventional optical element, lens or mirror, which is made by shaping a reflective or refractive surface, the diffraction optical element is made by recording in a suitable medium the interference pattern which occurs at the intersection of two coherent light wavefronts. The desired interference pattern is selected during design by simulating the optical performance of the finished diffraction element on a computer. The performance is then optimized on the computer by varying the construction wavefronts to be recorded. For head-up display combiners the interference pattern is recorded as curved layers (of varying index of refraction) within approximately 10 micron thick coating of gelatin. This gelatin coating is sandwiched between two layers of glass to protect it from abrasion and moisture. The optical function of the recorded diffraction lens results from the in-phase additions of multiple reflections of light incident on the gelatin coatings. The steps employed to make a diffraction optics combiner are listed in Table 6.

TABLE 6.

DIFFRACTION OPTICS COMBINER FABRICATION & PROCESSING STEPS

(1) Formulate the desired optical characteristics of the combiner and relay lens components by an interative computer aided design procedure.

(2) Procure the glass substrate and coat it with a uniform gelatin layer. This includes maintaining control on the gelatin quality and the film drying process.

(3) Process the gelatin layer so that it is uniformly sensitive to light.

(4) Assemble the optical components, (lenses, mirrors, lasers, beam splitters, baffles, etc.) necessary to construct the desired interference pattern.

(5) Expose the sensitized substrate to the laser wavefronts while maintaining the physical stability of the interference pattern to within 1/10th of a wavelength.

(6) Process the gelatin layer so that it is no longer light sensitive and so that the recorded interference pattern has maximum diffraction efficiency at the desired wavelength.

(7) Seal the recorded lens against moisture to prevent undesired shifts in operating wavelength.

(8) Grind the combiner to final size, affix mounts, and paint edges to reduce flare.

4. I-HUD DESIGN

In designing the HUD optics for the I-HUD system, it was desired to maximize the field of view consistent with the physical restraints of the aircraft and HUD performance. The instantaneous field of view was set by the size of the combiner and its distance from the design eye location. The vertical extent of the combiner is limited by the canopy and cowling lines. The vertical field of view can be increased by tilting the top of the combiner towards the pilot, but this increases the combiner bend angle as the main folding mirror must remain clear of the ejection envelope. A large combiner bend angle leads to a large variation in the efficiency of the diffraction optics combiner as the pilot vertically scans over the field of view. For a 50 degree bend angle (at the chief ray), a variation from 84 percent at the center to 65 percent at the edges would not be unusual. The horizontal field of view is related to the focal length of the combiner and the size of the folding mirror. The smaller the folding mirror size, the smaller the unit, but the smaller the combiner focal length, the larger the aberations in the combiner.

The size and focal length of the combiner were chosen to yield a suitable compromise between these factors based on the required eye relief, size and complexity of the relay lens, etc. The tilt of the diffusing screen and the relay lens elements were optimized to hold the optical aberations to less than one milliradian. The final design configuration was obtained by using a computer program to iterate and optimize all elements. The predicted residual aberations are shown in Tables 7, 8, and 9.

The field-of-view achieved in the I-HUD design is about 30% greater than that provided by the F-16 production HUD refractive optics. However, developments which have occured since the I-HUD design have extended the capabilities of diffraction optics significantly beyond even this level of improvement. It is not unreasonable to presume that all high performance HUDs of the future will utilize diffraction optics combiners.

TABLE 7.

ABERRATION - SPHERICAL AND FIELD CURVATURE

Definition - Variation in focal length from different locations in the aperture.

Results - Accuracy errors causing biocular disparity.

	ON AXIS		FULL FIELD	
	GOAL	DESIGN	GOAL	DESIGN
VERTICAL (MRAD)	1.0	0.5	1.0	1.5
HORIZONTAL DIVERGENT (MRAD)	1.0	0.0	1.0	1.0
HORIZONTAL DIVERGENT (MRAD)	1.0	1.0	2.5	2.0

TABLE 8.

ABERRATION - COMA

Definition - Variation in magnification from different locations in the aperture.

Results - Accuracy errors

	ON AXIS		FULL FIELD	
	GOAL	DESIGN	GOAL	DESIGN
ACCURACY ERRORS, MRAD	1.0	1.0	5.0	2.0

TABLE 9.

ABERRATION - ASTIGMATISM

Definition - Difference in focal length between the two planes of the system.

Results - Increase in blur circle or reduction in resolution.

	ON AXIS		FULL FIELD	
	GOAL	DESIGN	GOAL	DESIGN
RESOLUTION (MRAD)	1.0	0.3	1.0	0.3

SECTION X.

. TEST SUPPORT EQUIPMENT

1. BACKGROUND

The test support equipment consists of those subsystems necessary to test and demonstrate the I-HUD Pilot's Display Unit in the laboratory. In an operational aircraft installation, some of the circuitry in the test support equipment would not be required, while other func:ions would be incorporated into HUD System support equipment mounted in the equipment bays. To facilitate operation of the I-HUD System in the laboratory, this equipment has been configured to operate from a standard 117-volt, 60 hz power outlet and is compatible with either 525 or 875 line composite video television signal sources.

The outputs of the test support equipment are the signal and power forms required by the Pilot's Display Unit as shown in Figure 43. The signal interface is modeled after that established for the raster output of the DAIS Display System Memory Unit except that a phased locked sampling clock (element sync.) is provided to prevent jitter; in its absence the sampling clock free runs. The I-HUD Pilot's Display Unit was designed anticipating a 400 hz, 3-phase, 120/208 volt power source, but the unit will operate satisfactorily on the single phase 400 hz power provided. The dc power forms provided by the test support equipment are filtered and regulated. The only power conditioning circuit within the Pilot's Display Unit is a lamp power supply.

The test support equipment is mounted together in a single equipment rack. Figure 44 shows the equipment prior to the panels being painted and lettered. As shown the Test Support Equipment includes the Direct Support Unit, the Geometric Correction Unit and the Power Converter. (Note that although the COHU Camera Controller is mounted as a separate unit in the rack, it is considered part of the Geometric Correction Unit). Nc-mal air convection is sufficient to cool the equipment provided the top of the rack is not obstructed.

2. DIRECT SUPPORT UNIT

The Direct Support Unit provides those circuits necessary to convert a 525/875-line composite video signal to the DAIS format required by the Pilot's Display Unit and those circuits necessary to generate/control the requisite ac and dc power forms. The Direct Support Unit also includes a video function generator (Gamma Shaper) to match the electro-optic transfer curve of the liquid crystal display to the standard TV transfer curve. A functional block diagram of the Direct Support Unit is shown in Figure 45.

The +5, +18, and -18 volt power supplies internal to the Direct Support Unit are of the switching regulator type, and they will operate from 50 to 400 hz, 117 volt power sources. The 24 volt power form is derived from the +18 volt supply, and is used to provide a low current LSI circuit substrate bias potential. The common reference point for the powr supply return lines is +18 volts with respect to ground (chassis & earth) to eliminate the need for internal level shifters between the logic and analog circuits.

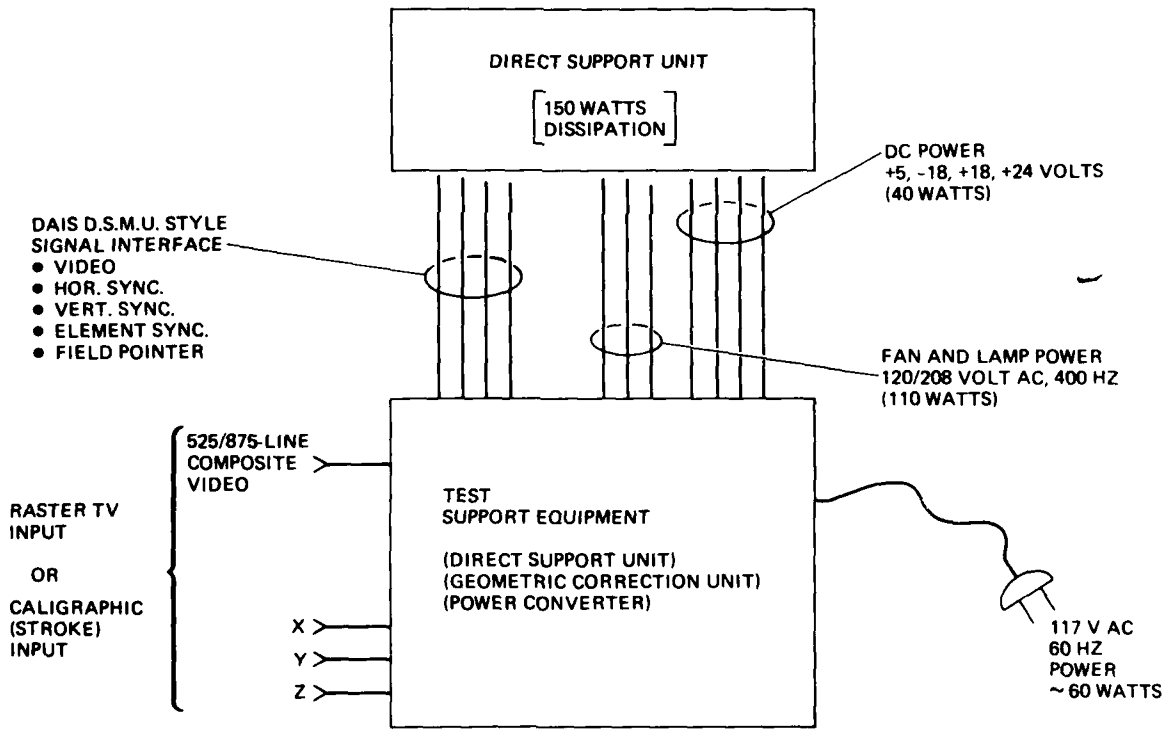

Figure 43. I-HUD system electrical interface summary.

A front panel control provides a means for inverting the video and therefore presenting the symbology on either a dark or light field. As the inversion follows the gamma shaper, optimum grey shade rendition can be obtained with only one polarity; the gamma shaper has been adjusted for the normal presentation of conventional TV video.

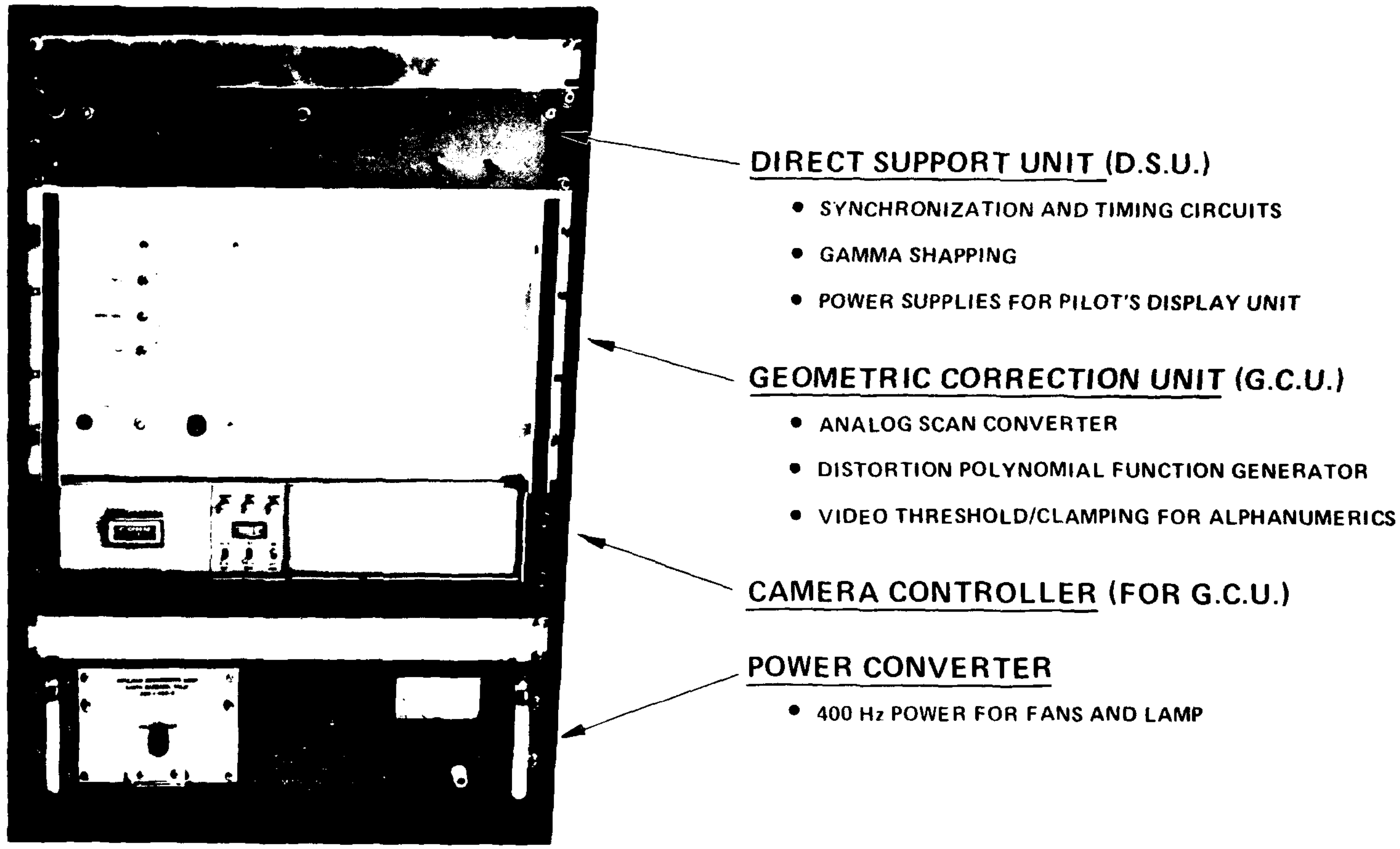

Figure 44. I-HUD test support equipment.

Front panel controls are also provided to adjust for the format of the input raster. The sampling rates have been adjusted to minimize the geometric distortion with 525-line interlaced formats and 875-line non-interlaced formats. When displaying X-Y-Z calligraphic symbology, the data is routed through the Geometric Correction Unit, and it has been set up to output an 875-line raster format to the Direct Support Unit.

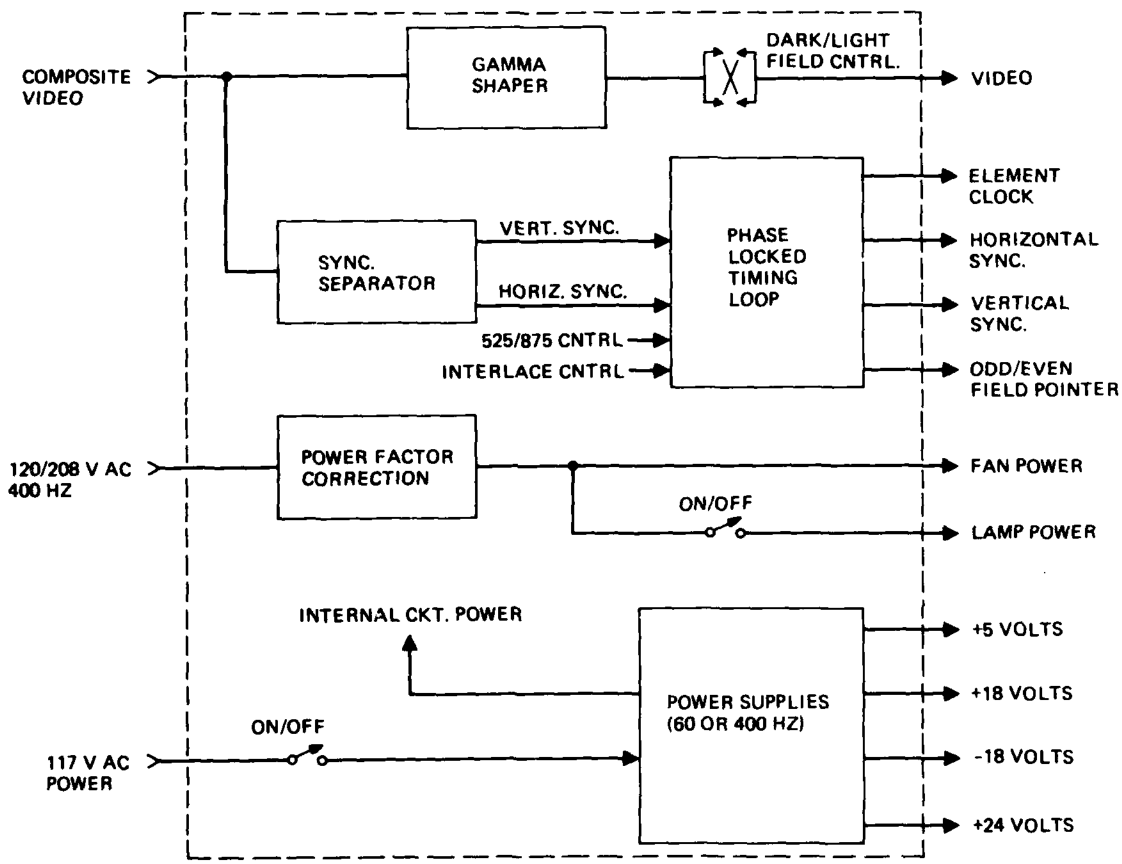

Figure 45. Direct support unit block diagram.

The Direct Support Unit also includes capacitors to correct the power factor of the lamp power supply and capacitors to shift the phase for fans. The power factor capitor has been sized such that the load is 220 VA at near zero leading power factor when the lamp is off and 210 VA at 65-degrees lagging power factor when the lamp is on. In this manner, a smaller converter (having only half the VA load rating) could be used than would be otherwise required.

3. POWER CONVERTER

To provide the 400 hz power required by the Pilot's Display Unit, a 60 to 400 hz power converter is included as part of the system. The Behlman Engineering Corporation Model 35-A-SA unit is rated at 350 volt-amps, and it includes a tapped auto-transformer for 120 and 208 volts. Care should be exercised to insure that the output is correctly set to 208 volts when the system is operated.

4. GEOMETRIC CORRECTION UNIT

The off-axis configuration of the collimator in the diffraction optics HUD portion of the I-HUD system introduces significant geometric distortion. To present an undistorted image to the viewer (pilot), a compensating predistorted image is formed on the diffusing screen. The image that must be formed on the liquid crystal matrix display is different still, as the projector optics partially compensates for the HUD optics distortion. The magnitude and type of geometric correction required is shown in Figure 46.

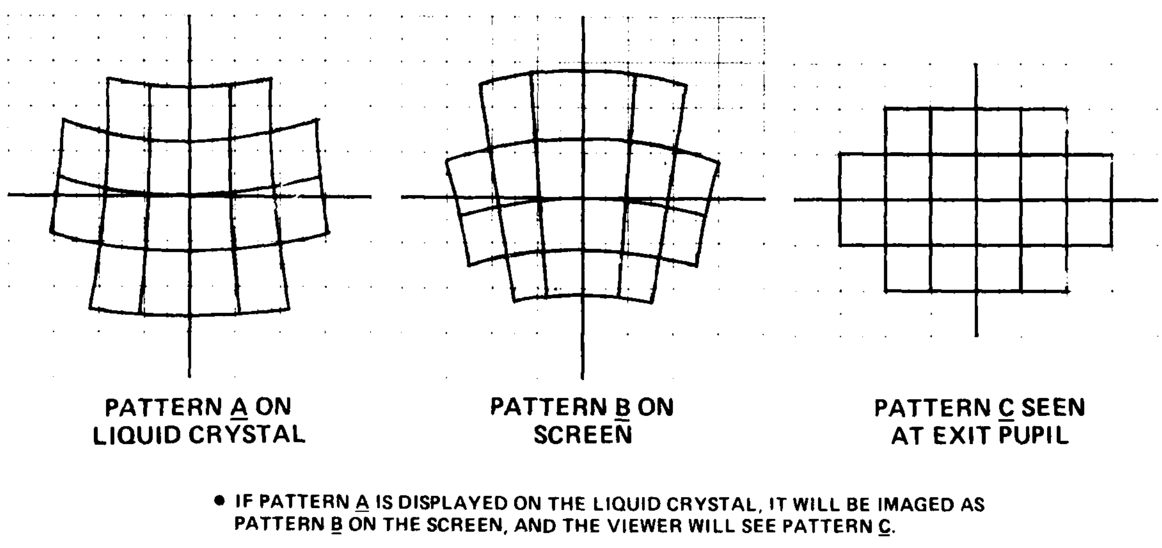

Figure 46. Geometric correction requirements.

To correct for this distortion, the Geometric Correction Unit shown schematically in Figure 47 has been included as part of the I-HUD system. The Geometric Correction Unit is fundamentally a simple analog scan converter. The horizontal and vertical deflection signals for the scan converter CRT are processed on by a group of function generators so that the image presented on the face of the CRT is predistorted in the required manner. A commercial COHU television camera is focused onto the screen of the CRT monitor, and the signals from it are used for generating the image presented on the liquid crystal matrix display.

The Geometric Correction Unit provides for converting calligraphic (X-Y-Z) or raster formatted display data. When the input is a raster formatted signal, the synchronizaton pulses are used to generate X and Y ramp signals that can be operated on by the function generators. For the improved presentation of symbology, a threshold and uniformity circuit is included to clamp the output video to either the black or white levels.

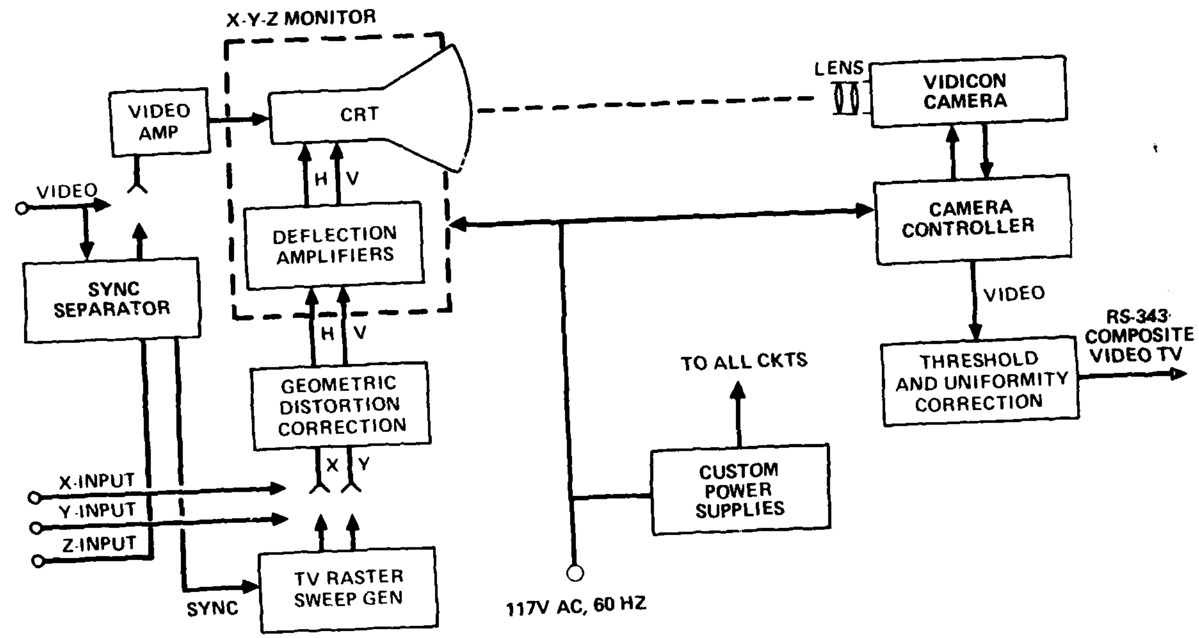

Figure 47. Geometric Correction Unit block diagram.

SECTION XI.

CONCLUSIONS & RECOMMENDATIONS

The I-HUD project has been a very ambitious program. An Air Force/Contractor team set forth to develop and functionally integrate into a single unit five state-of-the-art technologies: Liquid Crystal Matrix Display, LSI Matrix Display Drivers, Diffraction Optics, Specular Mode Liquid Crystal Projector, and Low Power Thallium Iodide Arc Lamp. Moreover, all of the above components were physically placed into a chassis approximately the size of the F-16 Pilot's Display Units to clearly demonstrate the feasibility of packaging the requisite hardware in a realistic volume.

A significant output of the I-HUD program is the attention now being given to diffraction optics diffusing screens for direct view applications. A diffraction optics diffusing screen was incorporated into the I-HUD Pilot's Display Unit because it solved certain problems associated with obtaining high screen gain at an angle far from normal to the surface, but it has since been realized that the low background scattering of a diffraction optics diffusing screen may lead to its use in a much wider range of applications. When used as a screen in directly viewed rear-projection systems, the ambient illumination does not significantly reduce the contrast ratio of the image as shown in Figure 48. The low back scatter level also means higher

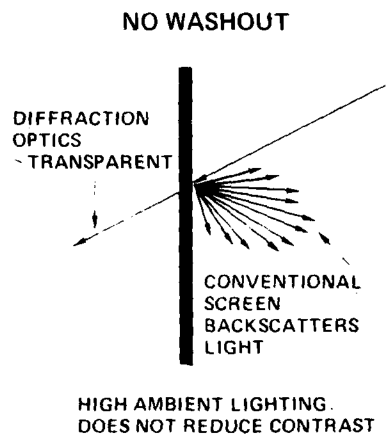

Figure 48. Diffraction optics diffuser in high ambient lighting.

AD-A104 337 HUGHES AIRCRAFT CO EL SEGUNDO CA DISPLAY SYSTEMS LAB F/G 14/5
STUDY AND DEVELOPMENT OF AN INTEGRATED HEAD-UP DISPLAY.(U)
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UNCLASSIFIED HAC-D6210 AFWAL-TR-81-1042 NL

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brightness because the attenuating filters normally required for contrast enhancement can be eliminated. These advantages are obtained in addition to the initial reason for its development, high screen gain. An experiment conducted while the Diffraction Optics Diffusing Screen for the I-HUD system was being tested showed that with a 50-watt thallium-iodide lamp based projector, 2000 ft-Lambert symbology could be obtained on the screen, and that the symbology was clearly visible when illuminated directly by 20,000 foot candles (a 1500-watt sun gun at one foot) or when viewed such that a 10,000 ft-Lambert surface was seen in the first surface reflection. The diffraction optics diffusing screen opens up a host of new applications including the potential for full color cockpit displays with performance significantly better than current CRT's.

Another result of the I-HUD program is an appreciation for the importance of redundancy and modularity in display construction. For the I-HUD Physical Quad Display to have been line defect free, perfection would have had to have been obtained in all 122,500 picture elements, 1408 wire bonds, 350 printed circuit substrate stripes, 1056 kapton cable circuit conductors, 1050 display line (row and/or column) drivers on 36 custom LSI chips, and all the other miscellaneous connectors and circuits. If instead of using a physical quad, the I-HUD had utilized four redundantly driven modules optically combined into a single image, the result would probably have been no line defects. Evidence in support of this position is shown in Figure 49 where the yield of line-defect free 175 by 175 arrays is compared for the cases with and without redundancy. For that case where each module averages two or less line opens per module, (all shorts having been converted to opens by laser trimming), the yield of acceptable (no line defects) modules is increased from 20-percent to 97-percent.

While performing the packaging design of the key I-HUD system components into a volume approximating that occupied by the F-16 Pilot's Display Unit, it became evident that a display surface comparable to that used for direct view applications is inappropriate. A liquid crystal matrix display two to three inches across would have permitted more compact packaging. In addition, additional resolution needs to be provided if the quantized nature of the matrix display is not to be objectionable. As a minimum, resolution comparable with 525-line television (480 x 640 pixels) is needed, with 875-line television resolution (750 x 1000 pixels) desirable for future wide-field-of- view installations. While improving resolution, the grey scale capability of the display should be maintained as it permits the display of forward looking infrared (FLIR) video.

The I-HUD brassboard, although not attaining all of it performance goals, clearly demonstrated the validity of the design approach. Symbol brightness levels of 1000 ft-lamberts in the combiner were achieved even with the handicap of high loss condensing optics and low efficiency diffusing screen. Implementing known techniques to improve these and other components would lead to an eight fold increase in brightness or an 8000 ft-lambert brightness image in the combiner. A raster head-up display of this brightness level would greatly effect the way Head-Up Displays are used, as daytime presentation of radar, FLIR and TV imagery would then become practical.

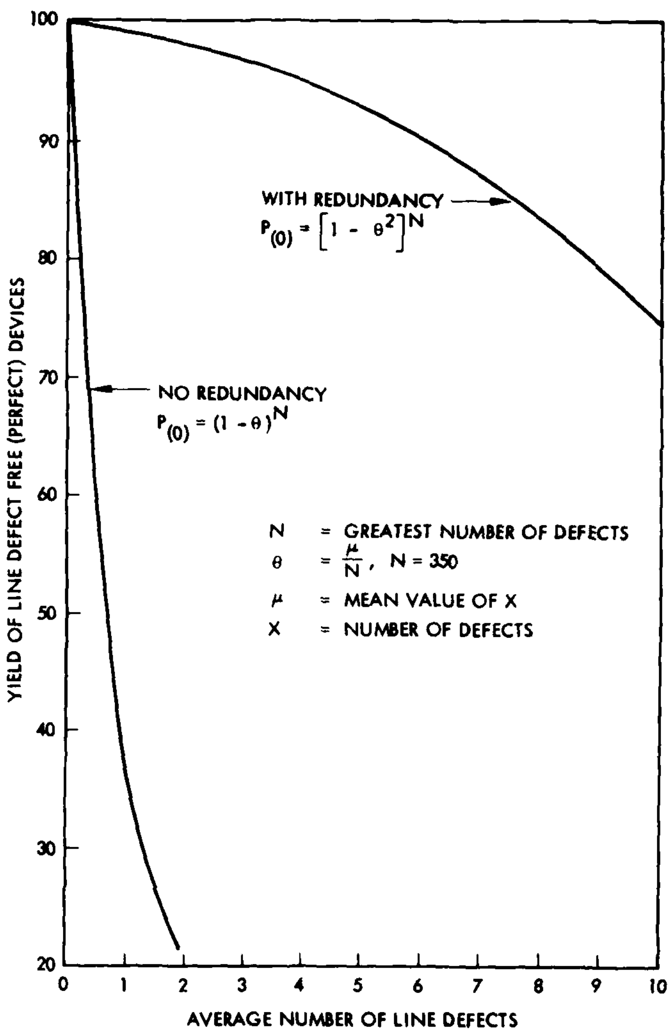

Figure 49. Impact of redundancy module yield.

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Appendix A

PARTS LIST

1. ALPHABETICAL LISTING OF PARTS

C3619006	400 HZ Power System
D3619073	Alignment Fixture, Diopter TLSCP mount.
D3619072B	Arc Lamp Mount
DP32257-021	Arc Lamp Power Supply Load Waveforms
D3608812	Back-up plate
D3608820/3	Board (PC) dimensions, sweep, video, pwr strobe, &sync. proc.
D3608820/2	Cable Dimensions, Sweep and Video for RMI/HSI design.
D3608814	Cable wedge - kapton cable connector pressure plate.
D3619015	Chassis front end assembly.
D3619076	Chassis front end housing.
D3619071	Chassis housing for P.D.U. controls.
D3619050	chassis housing, rear
D3619003	Chassis Machining Details except front end.
D3619003/1	Chassis, interior side details.
D3619003/2	Chassis, main structure.
D3619003/3	Chassis, rear housing & connector mounting
D3619003/4	Chassis, rear housing & connector mounting.
D3619003/5	Chassis, side & bottom covers
D3619003/6	Chassis, top cover, fan and lamp mount bracket
D3619048	Combiner alignment plate
D3619091	Combiner Assembly, Diffraction Optics
D3619088	Combiner ball, split
D3619086	Combiner clamp, lower ball.
D3619084	Combiner clamp, upper ball.
D3619031	Combiner construction optics, lens element I beam expander.
D3619033	Combiner construction optics, lens element II beam expander.
D3619059	Combiner construction optics, positioners
D3619049	Combiner construction optics, stand, optical mount
D3619058	Combiner construction optics, stand, optical mount
D3619085	Combiner rod, ball end
D3619081	Combiner, diffraction optics
D3619087-1	Combiner, holder
D3619049	Combiner, holder for same during exposure/construction
D3619083	Cover plate for combiner substrate.
SK030480	Demo Wiring Layout
D3619065	Dimmer, Adjustable Support
D3619068	Dimmer, Angle support
D3619063	Dimmer, fill roller spring
D3619069	Dimmer, film density pattern
D3619062	Dimmer, film roller drive
D3619064	Dimmer, film roller shaft
D3619061	Dimmer, line bore assembly
D3619067	Dimmer, Spacer
D3619066	Dimmer, Torsion Spring
D3619060	Dimming Assembly
D3596141	Direct Support Unit Chassis Wiring
DP32257-015	Direct Support Unit Front Panel]
C3596140-100	Direct Support Unit Identity Tag
C3596140	Direct Support Unit Mechanica` Layout
D3619011	DISPLAY ?
D3608810	Display Subassembly
D3619032	Display Surface Assembly, liquid crystal physical quad.
D3608820	Driver board and cable dimensions for RMI/HSI design.
DP32257-022	Electro-Pacific Arc Lamp Power Supply Schematic

D3619078	Filter, loss-less window
D3619095	Filter, UV for arc lamp
D3619080	Frame for loss-less window.
D3619092	Frame, Combiner, Diffraction Optics
D3619012	Frame, Quad Display Mounting & cable clamping
D3608813	Front Frame
C3596146	Gamma Correction Ckt Layout
C3596147	Gamma Correction Ckt Schematic
D3619090	Gasket for loss-less window frame.
DP32257-016	Geometric Correct Unit Front Panel Layout
DP32257-020	Geometric Correction Unit Block Diagram
D3596150	Geometric Correction Unit Chassis Layout
E3601970	Geometric Correction Unit Function Generator Layout
D3601971	Geometric Correction Unit Function Generator Schematic
C3596150-100	Geometric Correction Unit Identity Tag
C3596150-200	Geometric Correction Unit O & M
DP32257-017	Geometric Correction Unit Rear Panel Layout
E3601951	Geometric Correction Unit Sweep Generator
D3619013	Heat Exchanger for Quad Display
D3619005-ref	I-HUD Electrical layout for pilots display unit.
SK2359	I-HUD Optical Layout
D3619000-500	Installation control drawing
D3619020-ref	Kapton cable layout for I-HUD
D3608835-QLCD2	Kapton Cabling, sweep
D3619025-QLCD1	Kapton cabling, sweep
D3619026	Kapton Cabling, sweep
D3619021	Kapton cabling, video
D3608836	Kapton Cabling.
DP128100	Lamp Connector, contact clip
DP128102	Lamp Connector, high voltage insulator
DP128101	Lamp Connector, outside sleve
D3619027	Lamp support bracket
D3619096	Lens, projector aspheric
D3619036	Lens, relay element I
D3619037	Lens, relay element II
D3619038	Lens, relay element III
D3619039	Lens, relay element IV
D3619040	Lens, relay element V
D3619094	Mirror, condensing behind arc lamp
D3619079	Mirror, main folding mirror.
D3619055	Mirror, projector folding.
D3619029	Mount for diffusing screen
D3619072C	Mount, aspheric lens
D3619072	Mount, aspheric projection lens
D3619056	Mount, projector folding mirror
DP32257-023	P.D.U. Wiring Chassis
D3619070	Panel, front control faceplate for P.D.U.
C3596148	Phase Lock Loop Layout
D3596145	Phase Lock Loop Schematic
SP 5245	Pilot's Display Unit
C3619001-100	Pilot's Display Unit Identity Tag
SP-323027	Pilot's Display Unit Cradle
D3619001X	Pilots Display Unit Assembly
D3619051	Pin guide on rear of chassis.

D3619002	Plate, identification - not drawn
D3619089	Plug, bonding for combiner
E3608840	Power Strobe (A9)
D3608842	Power Strobe Board Fab. details
D3608841	Power Strobe Schematic
D3608843	Power Strobe Stitch Weld Details
D3619030	Power Supply, high-voltage, O & M drawing.
D3619010	Quad Display, Liquid Crystal Matrix Display Physical Quad.
DP119125	Reflector mandrel (tooling)
D3608820/1	
D3619057	Reflector, eliptical of revolution
D3619035	Relay lens assembly drawing.
D3619047	Relay lens cap, threaded
D3619034	Relay lens clamp.
D3619041	Relay lens retainer, threaded.
D3619042	Relay lens spacer no. 1
D3619043	Relay lens spacer no. 2
D3619044	Relay lens spacer no. 3
D3619045	Relay lens spacer no. 4
D3619046	Relay lens spacer no. 5
D3619054	Relay lens support.
DP32257-019	Revised Ramp Generator Test Circuit
D3619016	Rough O & M of I-HUD P.D.U. Chassis
D3619077	Socket, arc lamp high voltage contact clip
D3619093	Socket, arc lamp high voltage contact insulation sleeve.
D3619074	Socket, arc lamp high voltage insulation sleeve jacket
D3619082	Substrates for combiner
D3619072A	Support plate for lamp & aspheric lens
D3608830-A6	Sweep Driver
D3608830-A5	Sweep Driver Board
D3608830-A7	Sweep Driver Board as per RMI/HSI
D3608830-A8	Sweep Driver Board as per RMI/HSI
D3608832	Sweep Driver Board Fab. details
D3608833	Sweep Driver Board PC Artwork
D3608831	Sweep Driver Board Schematic
D3619014-2	Sweep LSI driver assembly left side.
D3619014-1	Sweep LSI driver assembly right side
E3608840B	Sync Processor Option
E3608880	Sync. Processor Board (A10 RMI/HSI?)
D3608882	Sync. Processor Board Fab. details
D3608881	Sync. Processor Board Schematic *
D3608883	Sync. Processor Board stitch weld details.
C3596149	Sync. Separator Layout
D3596143	Sync. Separator Schematic
DP32257-018	Sync. Separator Test Circuit
D3619057T	Tooling, elliptical reflector (mandrel)
D3619000-100	Unit drawing
D3619000-200	* Unit schematic
D3619000-300	Unit wire list
D3608862	Unknown, may be vacant number.
D3608860-A1/2	Video Driver
D3608860-A3/4	Video Driver
D3619015	Video Driver Assembly

D3608861	Video Driver Schematic
D3608863	Video LSI driver PC board artwork
C3596153	Video Shaper Ckt
C3596152	Video Shaper Layout

2. NUMERICAL LISTING OF PARTS

C3596140	Direct Support Unit Mechanical Layout
C3596140-100	Direct Support Unit Identity Tag
D3596141	Direct Support Unit Chassis Wiring
D3596143	Sync. Separator Schematic
D3596145	Phase Lock Loop Schematic
C3596146	Gamma Correction Ckt Layout
C3596147	Gamma Correction Ckt Schematic
C3596148	Phase Lock Loop Layout
C3596149	Sync. Separator Layout
D3596150	Geometric Correction Unit Chassis Layout
C3596150-100	Geometric Correction Unit Identity Tag
C3596150-200	Geometric Correction Unit O & M
C3596152	Video Shaper Layout
C3596153	Video Shaper Ckt
E3601951	Geometric Correction Unit Sweep Generator
E3601970	Geometric Correction Unit Function Generator Layout
D3601971	Geometric Correction Unit Function Generator Schematic
D3608810	Display Subassembly
D3608812	Back-up plate
D3608813	Front Frame
D3608814	Cable wedge - kapton cable connector pressure plate.
D3608820	Driver board and cable dimensions for RMI/HSI design.
D3608820/1	
D3608820/2	Cable Dimensions, Sweep and Video for RMI/HSI design.
D3608820/3	Board (PC) dimensions, sweep,video,pwr strobe,&sync.proc.
D3608830-A5	Sweep Driver Board
D3608830-A6	Sweep Driver
D3608830-A7	Sweep Driver Board as per RMI/HSI
D3608830-A8	Sweep Driver Board as per RMI/HSI
D3608831	Sweep Driver Board Schematic
D3608832	Sweep Driver Board Fab. details
D3608833	Sweep Driver Board PC Artwork
D3608835-QLCD2	Kapton Cabling, sweep
D3608836	Kapton Cabling.
E3608840	Power Strobe (A9)
E3608840B	Sync Processor Option
D3608841	Power Strobe Schematic
D3608842	Power Strobe Board Fab. details
D3608843	Power Strobe Stitch Weld Details
D3608860-A1/2	Video Driver
D3608860-A3/4	Video Driver
D3608861	Video Driver Schematic
D3608862	Unknown, may be vacant number.
D3608863	Video LSI driver PC board artwork
E3608880	Sync. Processor Board (A10 RMI/HSI?)
D3608881	Sync. Processor Board Schematic
D3608882	Sync. Processor Board Fab. details
D3608883	Sync. Processor Board stitch weld details.
D3619000-100	Unit drawing
D3619000-200	* Unit schematic
D3619000-300	Unit wire list
D3619000-500	Installation control drawing
C3619001-100	Pilot's Display Unit Identity Tag
D3619001X	Pilots Display Unit Assembly

D3619002	Plate, identification - not drawn
D3619003	Chassis Machining Details except front end.
D3619003/1	Chassis, interior side details.
D3619003/2	Chassis, main structure.
D3619003/3	Chassis, rear housing & connector mounting
D3619003/4	Chassis, rear housing & connector mounting.
D3619003/5	Chassis, side & bottom covers
D3619003/6	Chassis, top cover, fan and lamp mount bracket
D3619005-ref	I-HUD Electrical layout for pilots display unit.
C3619006	400 HZ Power System
D3619010	Quad Display, Liquid Crystal Matrix Display Physical Quad.
D3619011	DISPLAY ?
D3619012	Frame, Quad Display Mounting & cable clamping
D3619013	Heat Exchanger for Quad Display
D3619014-1	Sweep LSI driver assembly right side
D3619014-2	Sweep LSI driver assembly left side.
D3619015	Chassis front end assembly.
D3619015	Video Driver Assembly
D3619016	Rough O & M of I-HUD P.D.U. Chassis
D3619020-ref	Kapton cable layout for I-HUD
D3619021	Kapton cabling, video
D3619025-QLCD1	Kapton cabling, sweep
D3619026	Kapton Cabling, sweep
D3619027	Lamp support bracket
D3619029	Mount for diffusing screen
D3619030	Power Supply, high-voltage, O & M drawing.
D3619031	Combiner construction optics, lens element I beam expander.
D3619032	Display Surface Assembly, liquid crystal physical quad.
D3619033	Combiner construction optics, lens element II beam expander.
D3619034	Relay lens clamp.
D3619035	Relay lens assembly drawing.
D3619036	Lens, relay element I
D3619037	Lens, relay element II
D3619038	Lens, relay element III
D3619039	Lens, relay element IV
D3619040	Lens, relay element V
D3619041	Relay lens retainer, threaded.
D3619042	Relay lens spacer no. 1
D3619043	Relay lens spacer no. 2
D3619044	Relay lens spacer no. 3
D3619045	Relay lens spacer no. 4
D3619046	Relay lens spacer no. 5
D3619047	Relay lens cap, threaded
D3619048	Combiner alignment plate
D3619049	Combiner construction optics, stand, optical mount
D3619049	Combiner, holder for same during exposure/construction
D3619050	chassis housing, rear
D3619051	Pin guide on rear of chassis.
D3619054	Relay lens support.
D3619055	Mirror, projector folding.
D3619056	Mount, projector folding mirror
D3619057	Reflector, eliptical of revolution
D3619057T	Tooling, elliptical reflector (mandrel)
D3619058	Combiner construction optics, stand, optical mount

D3619059	Combiner construction optics, positioners
D3619060	Dimming Assembly
D3619061	Dimmer, line bore assembly
D3619062	Dimmer, film roller drive
D3619063	Dimmer, fill roller spring
D3619064	Dimmer, film roller shaft
D3619065	Dimmer, Adjustable Support
D3619066	Dimmer, Torsion Spring
D3619067	Dimmer, Spacer
D3619068	Dimmer, Angle support
D3619069	Dimmer, film density pattern
D3619070	Panel, front control faceplate for P.D.U.
D3619071	Chassis housing for P.D.U. controls.
D3619072	Mount, aspheric projection lens
D3619072A	Support plate for lamp & aspheric lens
D3619072B	Arc Lamp Mount
D3619072C	Mount, aspheric lens
D3619073	Alignment Fixture, Diopter TLSCP mount.
D3619074	Socket, arc lamp high voltage insulation sleeve jacket
D3619076	Chassis front end housing.
D3619077	Socket, arc lamp high voltage contact clip
D3619078	Filter, loss-less window
D3619079	Mirror, main folding mirror.
D3619080	Frame for loss-less window.
D3619081	Combiner, diffraction optics
D3619082	Substrates for combiner
D3619083	Cover plate for combiner substrate.
D3619084	Combiner clamp, upper ball.
D3619085	Combiner rod, ball end
D3619086	Combiner clamp, lower ball.
D3619087-1	Combiner, holder
D3619088	Combiner ball, split
D3619089	Plug, bonding for combiner
D3619090	Gasket for loss-less window frame.
D3619091	Combiner Assembly, Diffraction Optics
D3619092	Frame, Combiner, Diffraction Optics
D3619093	Socket, arc lamp high voltage contact insulation sleeve.
D3619094	Mirror, condensing behind arc lamp
D3619095	Filter, UV for arc lamp
D3619096	Lens, projector aspheric
SK030480	Demo Wiring Layout
SK2359	I-HUD Optical Layout
SP 5245	Pilot's Display Unit
SP-323027	Pilot's Display Unit Cradle
DP128100	Lamp Connector, contact clip
DP32257-023	P.D.U. Wiring Chassis
DP32257-015	Direct Support Unit Front Panel]
DP32257-016	Geometric Correct Unit Front Panel Layout
DP32257-017	Geometric Correction Unit Rear Panel Layout
DP32257-018	Sync. Separator Test Circuit
DP32257-020	Geometric Correction Unit Block Diagram
DP32257-021	Arc Lamp Power Supply Load Waveforms
DP32257-022	Electro-Pacific Arc Lamp Power Supply Schematic
DP32257-019	Revised Ramp Generator Test Circuit

DP128101	Lamp Connector, outside sleve
DP128102	Lamp Connector, high voltage insulator
DP119125	Reflector mandrel (tooling)

APPENDIX B
LIQUID CRYSTAL MATERIAL CHARACTERISTICS

1. INTRODUCTION

Liquid crystals (LX's) are organic substances which act like liquids over a specific range of temperature, while retaining some properties of crystals. Below the liquid crystal temperature range, the material becomes solid; above this range, it loses its crystalline properties and behaves like a true liquid. In the intermediate LX range, however, it passes through a turbid liquid state, which is termed the mesomorphic or "liquid crystal" state. The molecular arrangement in the liquid crystal state is more orderly than in the liquid state but less orderly than in the solid state.

The temperature range for the liquid crystal state varies with liquid crystal materials, and considerable effort has been devoted to developing materials which have liquid crystal properties over a wide range of temperatures, including normal room temperature.

Liquid crystals have been classified in three basic categories: nematic, smectic, and cholesteric. The terms denote characteristic spatial configurations assumed by the molecules of these materials. While the molecules of cholesteric LX's are optically active, those of nematic and smectic LX's are generally optically inactive, (i.e., they do not rotate polarized light).

Nematic LX's consist of rod-like molecules aligned in parallel, similar to matches in a box; it is this type of material that is presently used in the Hughes LX display. Each molecule can rotate only around its long axis and has limited freedom of movement from side to side or up and down (Figure B - la). The smectic LX's have a layered arrangement. The layers can

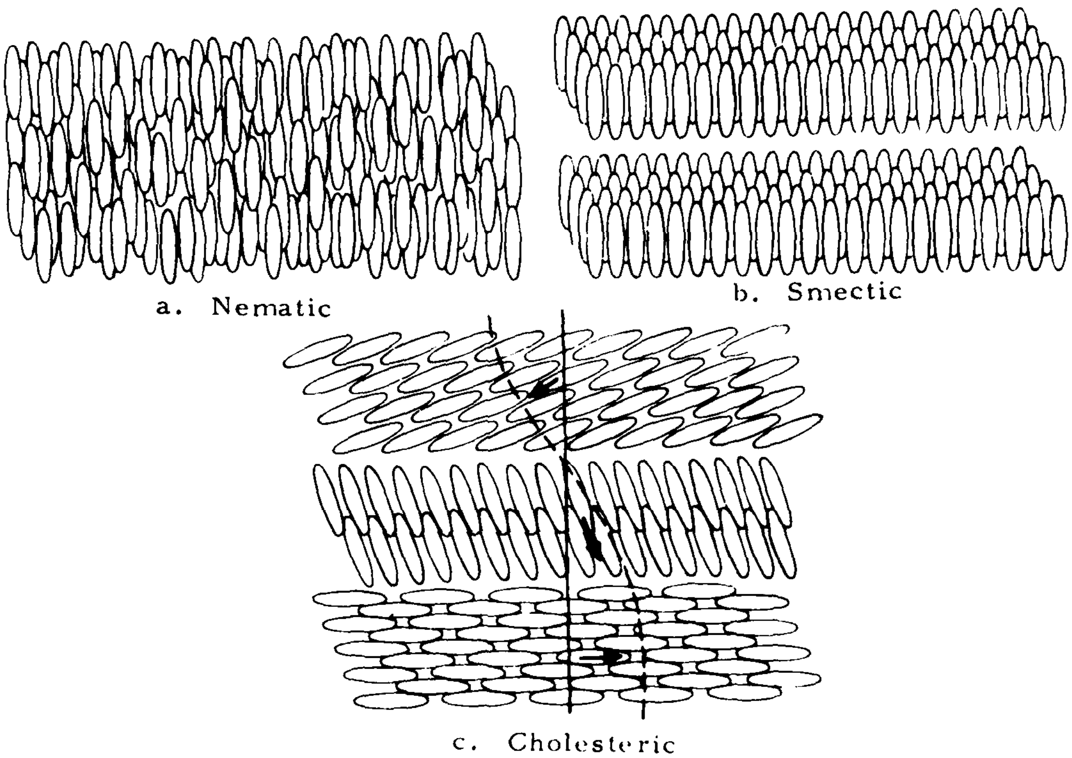


Figure B-1. Diagrams of packing effects in liquid crystals.

slide over one another, because the molecules in each layer can move from side to side or forward and backward but not up and down. Within each layer, molecules may be ordered in ranks (Figure B-1b) or randomly distributed. The cholesteric, like the smectic, LX's consist of layers. Within each layer, however, the molecules are parallel, as are the nematic molecules. Molecules in one layer influence the layers above and below, so that the long axes of the molecules in these layers are displaced slightly and a helical pattern forms from layer to layer (Figure B-1c).

A very important property of liquid crystals is the dielectric anisotropy, $\Delta\epsilon$, a quantity used to describe the orientation of liquid crystal molecules in the presence of electric fields.

$$\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp} \tag{1}$$

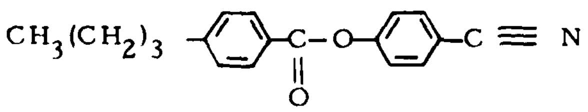
where:

$\epsilon_{\parallel}$ = dielectric permittivity in a direction parallel to the long axis of the LX molecule

$\epsilon_{\perp}$ = dielectric permittivity in a direction perpendicular to the long axis of the molecule

Equation (1) describes the <u>static</u> dielectric behavior and is most useful in evaluationg the molecular behavior or figure of merit for LX materials utilized for display purposes.

In general, when $\Delta\epsilon$ is positive, the molecular axis aligns roughly in the direction of an electric or magnetic field, whereas when $\Delta\epsilon$ is negative, the molecules orient themselves at an angle roughly perpendicular to the field. For the molecules of the LX substances used for airborne display, only the electric field strength is of interest. The dielectric anisotropy is a function of the vector sum of the dipolar groups in the molecule. To prepare an LX with a strongly positive $\Delta\epsilon$, for example, it is conventional to introduce the strongly dipolar nitrile group at the end of the long axis of the molecule, as in



Individual properties of each of the types of LX's have been utilized in making displays. The properties associated with each type of LX material are listed below.

NEMATICS:	Dynamic scattering Field effects (1) Twisted Nematic (2) Birefringent color switch (3) Nematic dichroic dye interaction
CHOLESTERICS:	Reflective color displays (1) Temperature sensitive (2) Pressure sensitive (3) Chemical vapor sensitive (4) Electric field sensitive
SMECTICS:	Thermo-optic storage display
HYBRIDS:	Thermo-optic Cholesteric-nematic phase change

a. Dynamic Scattering Mode (DSM)

Briefly, DSM may be characterized by electrical current — field induced hydrodynamic motion. Nematic LX's are optically anisotropic (i.e., they have different refractive indices for directions parallel to and perpendicular to the long axes of the molecules.) The effect of applying a voltage to and passing a current through a typical LX cell (see Figure B-2) is to disrupt the normally uniform molecular orientation in favor of a large number of small regions (domains) whose molecular orientation is different from those of their neighboring domains. The effect on light passing through the cell is that of closely spaced refractive index boundaries. These index boundaries refract the light at various angles (i.e., scatter it). The result is a system that is optically homogeneous and transparent when no voltage is applied and highly diffusing or scattering when voltage is applied.

DSM can be activated by either AC or DC signals. When AC is used, the frequencies are typically less than 1 KHz. The voltage value is dependent upon the material constituency and classification and ranges from

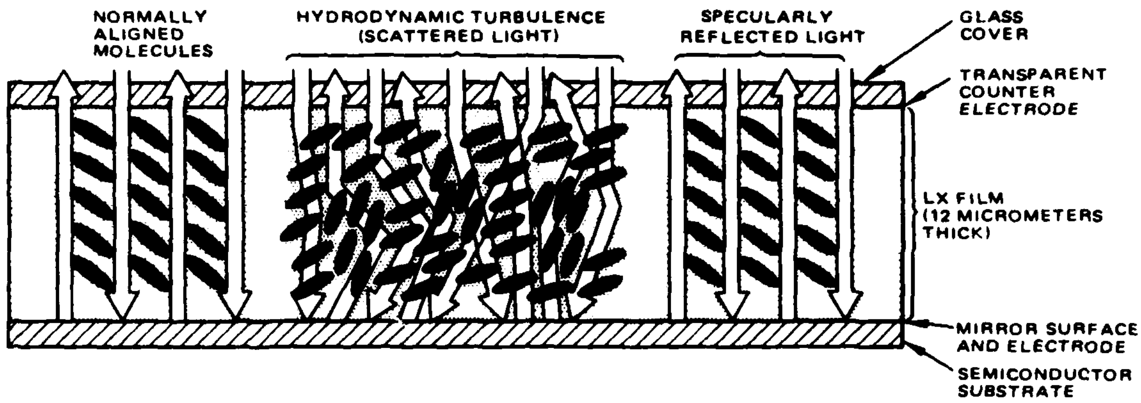


Figure B-2. Nematic LX shown in dynamic scattering mode (DSM)

0.5 volt to 60 volts. In the Hughes LX matrix display, the excitation is unipolar and of varying amplitude (22 volts or less) depending upon video scene content. An AC bias of 60 volts peak to peak amplitude and appropriate frequency (depending upon material constituency) helps return the molecules to their normally aligned state after the excitation is removed.

b. Field Effects

Another way to take advantage of the sympathetic alignment and the optical anisotropy of nematics is the twisted nematic configuration shown in Figure B-3. The design of the twisted nematic cell is the same as for the DSM, except that the cell walls are treated to make long axes of the LX's parallel to the plane of the cell wall. As result, on each cell wall the long axes of the LX molecules are parallel to each other as well as to the plane of the cell wall. The cell is assembled to form an angle of 90° between the direction of the long axes of the LX's on one wall and the corresponding direction on the other wall. Calculations show that the orientation of the long axes of the molecules varies smoothly across the cell thickness from one orientation to the other. Hence, the name twisted nematic.

If light incident on the cell is plane polarized either along the direction parallel to the long molecular axis or perpendicular to it, the plane of polarization of the light emerging from the other side of the LX cell is rotated 90°.

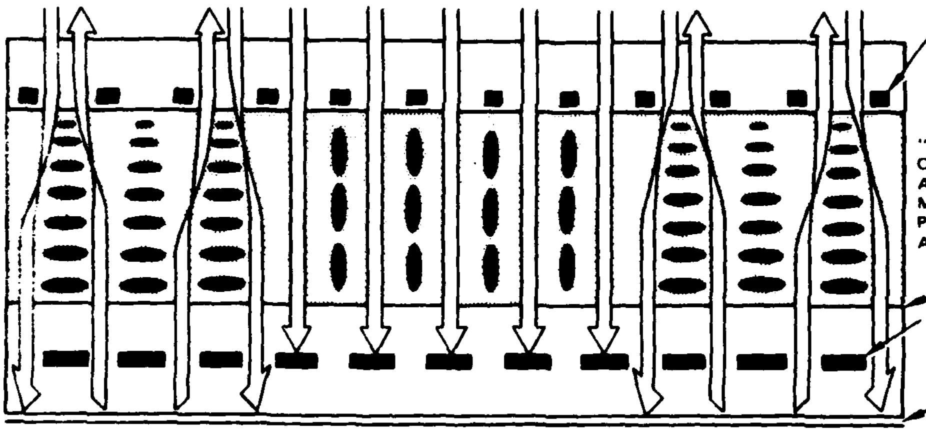


Figure B-3. Twisted Nematic LX shown in field effect mode.

When viewed through a polarizer oriented normal to the analyzer, this emerging light is observed to pass through the polarizer. However, if a field of sufficient strength (typically a few volts) is applied to the cell, light is blocked by the analyzer. The reason is that the molecules in the bulk change their alignment with the cell wall from parallel to perpendicular. As a result, no rotation of the plane of polarization of the light occurs when the field is applied. Since the analyzer is aligned normal to the polarizer, light is now blocked. Thus, by using a linear polarizer and analyzer in conjunction with a twisted nematic configuration, the intensity of the transmitted (polarized) light can be modulated with an electric field; hence the term "field effect," as opposed to DSM which is a current induced effect.

In their present state of development, nematic materials operated in the dynamic scattering mode, offer the most promising application to the matrix display technique described in this report. However field effect operation would be equally desirable if there were a practical method of applying a polarizer to the reflective surface of the matrix display substrate.

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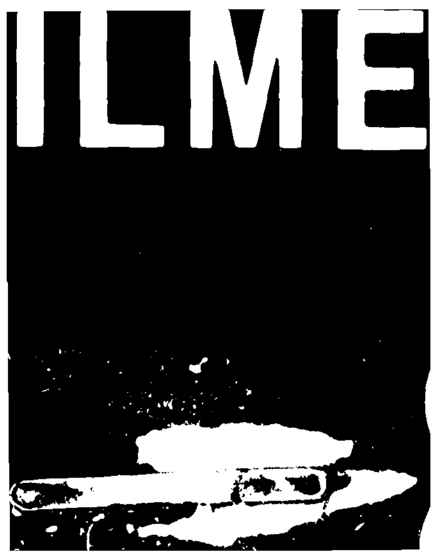
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